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ADHESION BETWEEN SOLID PARTICLES AND SOLID SURFACES

By

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I. SUMMARY

This investigation was undertaken to determine the magnitude of the forces with which particles, especially particles likely to be found in polluted atmospheres, adhere to the surfaces of buildings, plant leaves, and the like. Accordingly, a centrifugal-force technique was used to measure forces between particles such as sand, charcoal, rubber, and (for standardization) glass spheres and solids such as brick, wood, plastic, glass, metals, and vegetation leaves. The measurements were made at high, low, and intermediate relative humidities in order to evaluate the effect of this variable.

As expected, a great variation of forces was found to exist with every combination of particles and solid. Focusing attention, however, on size distribution changes as a function of forces applied to numbers of particles, it was possible to achieve consistent and meaningful data. These distributions and the changes they underwent are presented in tabular and diagrammetric form and are not subject to summarizing. Individual particle forces were calculated, nevertheless, and were shown to agree reasonably well with adhesion values obtained previously. Other calculations were made showing that such high-frequency vibrations and high wind velocities are necessary to dislodge some particles that natural phenomena, exclusive of precipitation, can never cause reentrainment of more than a portion of particle debris once it becomes attached to buildings, vegetation, and other surfaces. The results indicate, as also might be expected, that electrostatic forces play an important part in adhesion at low humidity while liquid water's surface tension is important at high humidity where condensed films can exist. Under high humidities, soluble materials may dissolve,

forming ions and thus give rise either to a repulsive or an attractive force to counteract partially or to enhance the surface tension force.

As there must be considered in particle adhesion a great many factors, such as electrostatics, solubility, particle shape, surface films, etc., it is recommended that any future investigation concentrate on materials having specific properties. The techniques of this study are regarded as sufficient for obtaining adhesion information.

II. INTRODUCTION

The aims of this work have been to determine the magnitude of the forces with which solid particles, particularly those representative of the debris found in the atmosphere, adhere to solid surfaces, and to establish the effect of such factors as the nature of the material and relative humidity on the adhesive forces. This type of information is of special importance in air pollution study and control, an example of concern at the moment being the sticking of radioactive particles to buildings, aircraft, automobiles, etc. and its possible reentrainment due to atmospheric changes.

Many variables affect the adhesion forces between solid particles and plane surfaces. Among these are area of contact, static electricity, relative humidity, type of material, dielectric constants, aggregation of particles, and others. It is apparent that some of the variables can neither be measured nor can their values be controlled. For example, it is presently impossible to determine experimentally the actual contact area between two particles or a particle and a solid surface. This inability to control and measure certain important variables would lead to uncertainties and great variations in any calculated forces of adhesion between particles and surfaces if particles were treated on an individual basis. By investigating the behavior of many particles at one time, consistent average values were obtained in this study.

First efforts of this investigation involved a thorough review of the literature on particle-to-particle and particle-to plate adhesion. Such fundamental and theoretical information as could be found is presented in the pages immediately following. Experimental work, comprising the body of the report, is then given. Numerous experiments under several conditions were conducted. Changes in the size distribution of the particles remaining

attached were measured after all particles had been subjected to a force tending to detach them. External conditions, e.g., relative humidity, were established well before each test and were maintained during the test.

III. THEORETICAL TREATMENT OF ADHESION FORCES

A. General Considerations

Solid particles exert an attractive force on each other unless they carry a sufficient electric charge of the same sign to neutralize the attraction or unless they are pressed together so closely that the electronic orbits of their respective atoms effect a repulsive force. Similarly, there exists between a particle and a solid plane surface an attractive force such as would exist between a pair of particles, one of which is infinitely large. These forces of attraction, or adhesion, are many orders of magnitude greater than the gravitational forces between the two particles when the above mentioned two factors are absent. However, the forces of adhesion are considered negligible at distances greater than 1×10^{-8} cm.[1]

B. London-van der Waals Forces

Forces of attraction can be traced to electric interactions between electronic charges in the atoms of the two particles. However, if this method of attacking the problem of adhesion is pursued, it will be found that more information is generally required than is available at the present time. Therefore the usual practice is to treat the forces of adhesion between solid particles in a more approximate manner. One of the best known approximate methods is the one depending upon the London-van der Waals dispersion forces.

London-van der Waals forces are always operative between particles of all shapes and sizes regardless of the chemical composition of the particles.

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[1] H. J. Lowe and D. H. Lucas, "The Physics of Electrostatic Precipitation," Brit. J. Appl. Physics, Supp. 3, S40-46 (1953).

Like the force of gravity, they can not be altered to any appreciable extent by the experimenter. Although a method for calculating forces of attraction between two spherical atoms or molecules has been established, the derived expressions have not been fully verified experimentally for non-spherical molecules or for solid particles of any size or shape. The equation for calculating the force of adhesion between two macroscopic spherical particles as derived by Bradley[2] and Hamaker[3] is

$$F = (\pi)^2 q^2 (\lambda)/12 x^2 (d_1 d_2/d_1 + d_2) \text{ dynes} \qquad (1)$$

where x = the distance of separation (assumed to be approximately 3×10^{-8} cm when the two particles are in contact),

λ = the London-van der Waals constant,

q = the number of atoms contained in 1 cm^3 of the substance,

and d = the diameter of the spherical particle in cm.

The value of $(\pi)^2 q^2 (\lambda)$ varies from about 10^{-11} to 10^{-13} ergs for most of the substances studied.

The London-van der Waals expression for the force of attraction between a sphere and flat plate may be obtained by allowing the diameter of one of the spheres in the above expression to become infinite. The equation modified for the case of the sphere and flat plate thus becomes

$$F' = (\pi)^2 q^2 (\lambda)/12 x^2 \; d \text{ dynes}, \qquad (2)$$

where the symbols have the same signifance as in the previous expression.

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[2] R. S. Bradley, "The Cohesive Forces Between Solid Surfaces and the Surface Energy of Solids," Phil. Mag. 13, 853-62 (1932).

[3] H. C. Hamaker, "The London-van der Waals Forces Between Spherical Particles," Physica. 4, 1058-72 (1937).

In the absence of static electric charges and water vapor, the primary forces of adhesion should be those due to the London-van der Waals dispersion forces. In the case of high humidity or low humidity with high static charges on the particles the London-van der Waals forces may play only a minor role in the over-all adhesive forces.

C. Actual Contact Area as Opposed to Apparent Contact Area

1. Geometrical Shapes

The principal influence of geometric shape on adhesion between solid particles will be its effect on the area of contact, especially in the case of perfectly smooth surfaces. The influence of geometric shape may be seen from the information given in Table I. The sphere and each of the regular polyhedra are assumed to contain 1.5708×10^{-12} grams of material with a density of 3.0 grams per cm^3. In addition, such shapes as laths,

TABLE I

CONTACT AREAS OF DIFFERENT GEOMETRICAL SHAPES

Geometric Shape of Particle	Area of Face of the Figure
Tetrahedron	1.163×10^{-8} cm^2
Cube	0.650×10^{-8} cm^2
Octahedron	0.464×10^{-8} cm^2
Dodecahedron	0.278×10^{-8} cm^2
Icesahedron	0.166×10^{-8} cm^2
Sphere	0.000×10^{-8} cm^2

discs, plates, and flakes will show a still greater area of contact with a flat plate if the particles are of the same masses. As should be obvious,

the equilibrium position of a disc or flake on a flat plate provides the maximum area of contact and at the same time leads to the minimum drag resistance from an air stream. On the other hand, a spherical particle will be the least stable toward removal by an air stream.

It is an experimental fact that very thin particles and very small particles adhere to a flat plate with greater force than do thicker and larger particles. This is so because very thin particles can be more readily deformed to fit over larger areas than would be possible in the case of thicker particles. An important point emphasized by Bangham[4] is that fairly large forces of adhesion can bring about appreciable deformation of a thin solid particle, thus leading to still stronger forces of adhesion. Since the force of adhesion is proportional to the area of contact, if deformation increases the contact area by bringing together parts of the surface which had been only slightly separated, the force of adhesion is further increased and, in turn, leads to still greater deformation.

In many cases solid particles formed from crystalline substances will possess a simple geometric shape, whereas the small particles of amorphous materials will be quite irregular in shape due to the lack of cleavage planes in such materials. In many cases the small particles may actually be aggregrates of smaller particles, so that the geometric shape of the resulting complex is quite irregular in shape. The adhesion force of such an aggregrate would be expected to be different from that for a single particle of the same size and material.

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[4] D. H. Bangham, "Physical Processes Involved in Sintering," Trans. Soc. Glass Technology 31, 264-266 (1947).

2. Elastic and Plastic Properties

The elastic and plastic properties of solids also have an effect on the forces of adhesion between solid particles. Illustrative of this contention is a commercial process used to cold-weld together two pieces of a plastic metal, such as aluminum. The two surfaces are cleaned and then squeezed together by the application of high pressures. A brittle metal such as antimony can not be cold-welded by this technique. If one of two adjacent solid particles is plastic, the application of a slight pressure will increase the real contact area between them. This increased contact area results in a greater force of adhesion between the particles. An increase in plasticity induced by high temperatures is taken advantage of in powder metallurgy. In this process small, clean particles of metal are welded together by high pressures and at temperatures which, though high, are considerably under the melting point of the metal.

3. Surface Roughness

The principal effect of surface roughness on the force of adhesion between two particles is its influence on the real area of contact between the particles. All equations for the calculation of adhesion forces between solids are derived on the assumption that the particles have a regular geometric shape and that the surfaces are smooth down to the atomic level. From the practical standpoint, it appears to be almost impossible to obtain regular shapes from amorphous substances; also it is impossible to obtain surfaces which are smooth down to the atomic level. In the cleavage of an ideal crystal a surface is obtained with steps of several hundred Angstroms in height. Thus equations for the calculation of forces of adhesion between

solid particles are based on models which evidently do not exist in nature, and good agreement between the calculated and measured values are not to be expected.

Some surfaces are changed irreversibly at high humidities, as was demonstrated by Bradley[5]. This phenomenon is evidently due to the etching of the surface by water. A flat plate of macroscopic dimensions may be given various treatments which will reduce the surface roughness; however, for particles in the micron size range there is very little which can be done to reduce the surface roughness of the particles.

Some values for the roughness of certain substances are given in Table II.

TABLE II

SURFACE ROUGHNESS

Substance	Roughness
Steel polished with 600 grade carborundum paper	Irregularities about 1.0×10^{-5} cm
Finely turned copper surface	Irregularities about 5.0×10^{-4} cm
Cast iron	Irregularities about 2.0×10^{-3} cm
Cleaved mica	Steps up to 1.5×10^{-5} cm in height

D. Effect of Static Electricity

If the static electric charges on two adjacent particles are large and opposite in sign they lead to rather large forces of adhesion between the

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[5] R. S. Bradley, op. cit.

particles. The precise mechanism by means of which static electric charges are produced on solid particles is far from completely understood at the present time. In the case of particles of the same material, the distribution and sign of the charge in some cases appear to be a random phenomenon, while in other cases the sign seems to be determined by the particle size. The number of electronic charges on spherical particles at equilibrium varies approximately with the first power of the particle diameter.

Quite frequently a solid brought into contact with water will become either positively or negatively charged. The charge on the solid may arise by the adsorption of ions from the water, or by the water's etching ions of predominately one sign from the solid. For example, glass in contact with water is negatively charged, evidently due to the removal of sodium ions from the glass. It is practically impossible to build up an appreciable static electric charge on solid bodies when they are surrounded by a very humid atmosphere. Therefore, the effect of static electric charges on adhesion between solid particles may be neglected in atmospheres of high relative humidity.

Recent work reported by Derjaguin and associates[6] indicates much difficulty in removing static electric charges from adjacent particles in a very dry atmosphere even by means of X-rays. The elimination of static electric charges in many systems is difficult at low relative humidities.

In measuring long-range van der Waals forces between glass plates one micron apart Prosser and Kitchener[7] were able to counteract the effects of

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[6] B. V. Derjaguin, I. I. Abrikosova and E. M. Lifshitz, "Direct Measurement of Molecular Attraction Between Solids Separated by a Narrow Gap," Quart. Rev. Chem. Soc. 10, 295-329 (1956).

[7] A. P. Prosser and J. A. Kitchener, "Direct Measurement of Long-Range van der Waals Forces," Nature 178, 1339-40 (1956).

static electricity by use of a high-frequency discharge or by admission of some water vapor to the system. (Their results, 1.2×10^{-3} dyne/cm^2, agreed with Derjaguin's findings.)

E. Effect of Humidity and Adsorbed Gases

The humidity of the atmosphere surrounding two solid particles, or one particle and a plate, has a pronounced influence on the forces of adhesion between the two, provided both the particles, or the particle and plate, are wet by water. In those cases where one or both of the materials are not readily wet by water, the effect of humidity on the force of adhesion between the particles should be much less. The influence of humidity on adhesion is strongly dependent upon the particle shape. In the case of two flat particles the humidity should have a much greater effect than in the case of two spherical particles, or a sphere and a flat plate.

When both a particle and a plane surface are wet by water and are close together, it is possible for a film of water to form between the two at relative humidities well below 100 per cent. In fact, some experimental work indicates that at a relative humidity of 85 per cent the force of adhesion between two particles which are wet by water is the same as that for a relative humidity of 100 per cent. The functional relationship under conditions of high relative humidity between the force of adhesion and the diameter of the spherical particle resting on a flat plate is a complicated one because, if the film thickness to which all particles are exposed is identical, it will involve different fractional portions of the spherical diameter as indicated in Figure 1.

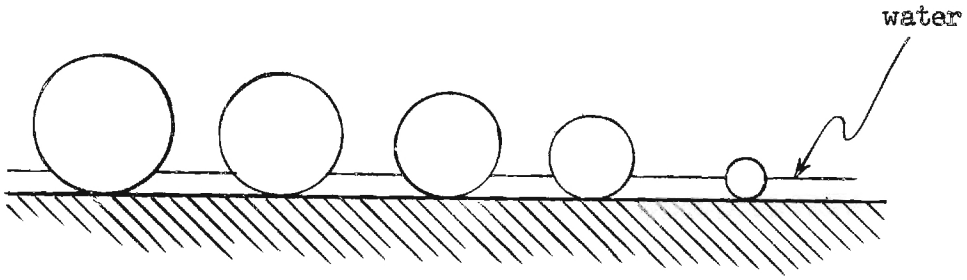

Figure 1. Water Film Between Spheres and Plate.

McFarlane and Tabor[8] have found the equation below applicable for the calculation of the force of adhesion between a sphere and flat plate having a film of water between them. The equation is based on the assumption that both the sphere and plate are wet by water.

$$F = 4 (\pi) R (\gamma) \qquad (3)$$

where F = force of adhesion in dynes,

R = radius of the water film surrounding the lower part of the sphere (in cm),

and γ = surface tension of water in dynes per cm (71.9 dynes per cm for water at 25° C).

Table III gives representative values calculated by equation 3. Table LVII in the Appendix lists some of the trigonometric relationships necessary in using equation 3. With the values in this table R may be readily determined for a given sphere on a flat plate covered by any thickness of water film. The accompaning equations and Figure 2 illustrate the use of the table.

Forces of adhesion at high humidities are free of contribution from static electricity, since negligible static electric charges can be built

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[8] J. S. McFarlane and D. Tabor, "Adhesion of Solids and the Effect of Surface Films," Proc. Roy. Soc. A202, 224-43 (1950).

TABLE III

ADHESION OF SPHERE AND PLATE SEPARATED BY WATER FILM

Radius of the Water Film (cm)	Force of Adhesion (dynes)
1.0×10^{-4}	0.09035
5.0×10^{-4}	0.45176
10.0×10^{-4}	0.90352
20.0×10^{-4}	1.80703
50.0×10^{-4}	4.51759
100.0×10^{-4}	9.03517

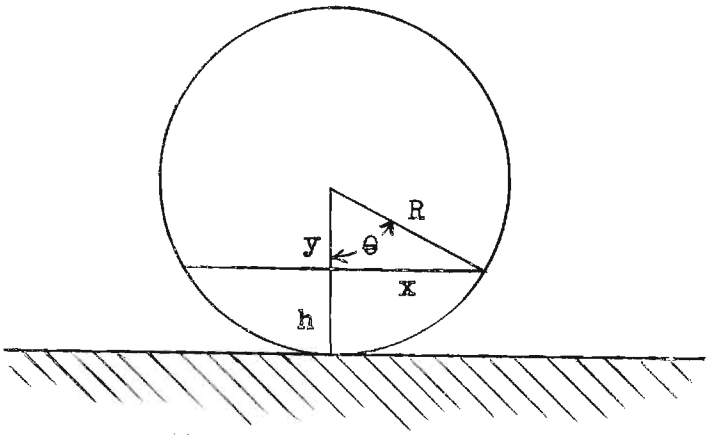

Figure 2. Some Trigonometric Relations for a Sphere Resting on a Plane. h = depth of water film = R (1 - cos θ); x = radius of water film = R sin θ.

up in humid atmospheres. Bowden and Tabor[9] have shown that the adhesion of a sphere to a plane surface, when a small amount of liquid is interposed

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[9] F. P. Bowden and D. Tabor, The Friction and Lubrication of Solids, Clarendon Press, Oxford (1950).

between the two surfaces, agrees with the theoretical value for spheres from 133 to 166 μ in diameter. The theoretical values were calculated with the equation

$$F_a = 2 \pi T_s D_s \qquad (4)$$

where F_a = the adhesion force perpendicular to the plane surface,

T_s = the surface tension of the liquid,

and D_s = the diameter of the sphere.

In studies of the adhesion of glass spheres to glass fibers Larsen[10] found that adhesion increased with increasing relative humidity. Removal of particles from the fibers by air flow at 40 per cent relative humidity required a velocity head ten times as great as that needed to remove them at 22 per cent relative humidity.

The effect of adsorbed nitrogen was studied by Howe and co-workers[11] who found that adsorbed gases decreased forces of adhesion between a glass bead and a plate of Pyrex glass. Large instantaneous adhesion forces were found using a freshly degassed apparatus. The force required to separate the bead from the plate was calculated from the equation

$$F = \frac{AD}{12\ d^2} \qquad (5)$$

where D = diameter of sphere,

d = shortest distance between sphere and plate,

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[10] Ralph I. Larsen, "The Adhesion and Removal of Particles Attached to Air Filter Surfaces," Amer. Ind. Hyg. Assn. J. 19, 265-270 (1958).

[11] P. G. Howe, D. P. Benton and I. E. Puddington, "London-van der Waals Attractive Forces between Glass Surfaces," Can. J. Chem. 33, 1375-83 (1955).

and A = force constant, estimated to be between 0.1 and 10 x 10^{-12} erg.

Friction is the result of adhesion forces. According to Bowden,[12] adsorbed air or water vapor diminishes the coefficient of friction, μ, for most metals, graphite, and diamonds. With Teflon, however, μ is always low, even when surface films of gases or vapors have been removed by heating or evacuation. Thus, while an evacuated system should increase the adherence of particles to metals, for example, it should have little effect on their adhesion to Teflon.

F. Other Variables

1. Dielectric Constants and Work Functions of Metals

When particles of two different dielectric materials are in contact, the particle with the larger dielectric constant usually carries a positive charge. For two different metallic particles in contact, the sign and magnitude of the charge seems to depend upon the work function of the metals. The metal with the larger work function becomes negatively charged, and the magnitude of the charge varies directly with the difference in work functions of the two metals. In the case of contact between a metal and a dielectric material, the production of an image charge will lead to a force of attraction, provided the dielectric particle carries a net electrical charge or has an unequal charge distribution on its surface. Figure 3 illustrates the inducement of an image force. The equation relating the force of attraction between a charged particle and the image charge which it induces in a metal is

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[12] F. P. Bowden, "Adhesion and Friction," Endeavour 16, 5-18 (1957).

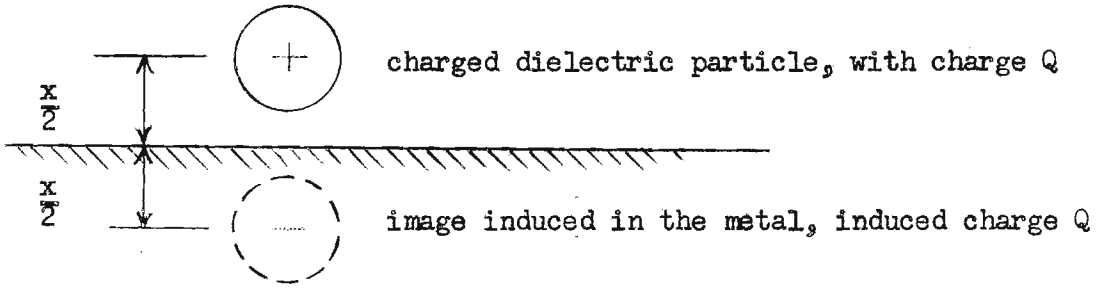

Figure 3. Image Force Induced in Metal by Dielectric Particle.
Distance between the two charges $= \frac{x}{2} + \frac{x}{2} = x$

$$F_i = \frac{Q^2}{D} X^2 \qquad (6)$$

where Q = the net electric charge on the particle in electostatic units,

D = the macroscopic dielectric constant of the medium between the charge and induced charge,

X = the distance between charge and induced charge in cm,

and F_i = the image force in dynes.

2. Aggregation of Particles

Forces of adhesion between a plate and a single particle of a material are probably different from forces between the plate and aggregates of the same material. An aggregate with the general form of a sphere 10 μ in diameter will contact an adjacent plate with an area unlike the contacting area of a perfect sphere of the same size and material. Also, being less rigid, the aggregate has a degree of plasticity and should adhere with a greater force than the single sphere. This effect may be overcome, however, when a plate attracts the particles comprising an aggregate less than the particles attract each other.

3. Tensile Strength

Lowe and Lucas[13] have studied the forces of adhesion between two spheres and between a sphere and a plane. They found the force opposing disruption of two spheres or disruption of a sphere and a plate to vary with the tensile strength of the material composing the particles, as shown by the equations

$$f = \pi U \frac{D_1 D_2}{(D_1 + D^2)} \times 10^{-8} \qquad (7)$$

for two spheres, and

$$f = \pi U D \times 10^{-8} \qquad (8)$$

for a sphere and a plate,

when U = tensile strength of materials,

and D = diameter of sphere.

The equations as written apply when the spheres or when the sphere and the plate are of the same material. When the two materials have different tensile strengths, the equations must be modified to take account of the relative contribution of each.

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[13] H. J. Lowe and D. H. Lucas, op. cit.

IV. EXPERIMENTAL INVESTIGATIONS AND RESULTS

In general terms, the experimental procedure of this investigation, in order, consisted of (1) sprinkling particles on a solid surface, or slide; (2) allowing the particles and surface to remain undisturbed under definite relative humidity conditions; (3) removing all superficially attached particles by tilting the plate; (4) determining the size of particles remaining on the plate by microscopic methods; (5) subjecting the plate and particles to a centrifugal force field acting to separate the particles from the plate; (6) remeasuring the remaining particle sizes; and (7) repeating steps 5 (at increasing rates of rotation) and 6 until few if any particles remained. These tests were carried out employing several combinations of material composing the particles and solid surfaces and at different humidities. Details of the tests are given in following sections.

A. Equipment and Conditions

A glove box was used for conditioning particles, slides, and centrifuge cells at desired relative humidities. The relative humidity inside the dry box was maintained at the desired level by means of various chemicals. Phosphorous pentoxide was used to produce a dry atmosphere of less than 10 per cent relative humidity. Magnesium nitrate in saturated solution with excess nitrate held the humidity between 48 and 53 per cent, and a saturated solution of sodium sulfate with excess sulfate maintained an atmosphere with relative humidities between 87 and 92 per cent. Static electricity was so prevalent in the very dry atmosphere that small strips of radioactive polonium, and in some cases radium D, were placed close to the slides and particles in an effort to neutralize the static charges.

A Fisher-Stern ultracentrifuge of the Fisher Scientific Co., Pittsburgh, Pa., powered by compressed air, was utilized to counteract the forces of adhesion. This centrifuge was mounted horizontally so that the slides in the centrifuge cells would have the same relative position at all times, perpendicular to the work bench. The radius of rotation for the slide and particles was 5.7 cm. The speed of rotation of the centrifuge was determined simultaneously by means of its attached tachometer and by a Strobotac unit of the General Radio Co., Cambridge, Mass., mounted over the centrifuge. One of the centrifuge cells containing a slide and adhering particles is pictured in Figure 4. The slide, approximately 13 mm long and 7 mm wide, was placed on the shelf inside the cell, where the overhang at each end of the shelf held it in place. Before removal from the glove box the cells were closed and sealed with high-vacuum stopcock grease to prevent the atmosphere inside the cell from being altered during the centrifuging step.

All size distributions were determined optically by means of a microscope with an attached optical micrometer. A magnification of 100X was used.

B. General Procedure

Solid particles and plates, or slides, of various materials were conditioned 40 hours, or longer, at the desired relative humidity before the particles were sprinkled onto the slides. After particles had been placed on a slide, the slide was gently turned through a 90-degree angle so that any loose particles would fall off. The size distribution of the particle sample was then determined. The slide with its sample was again conditioned four hours or longer at the initial humidity to permit reestablishment of conditions that might have changed while it was under the microscope and, of necessity, exposed to the atmosphere. It was next placed in a centrifuge

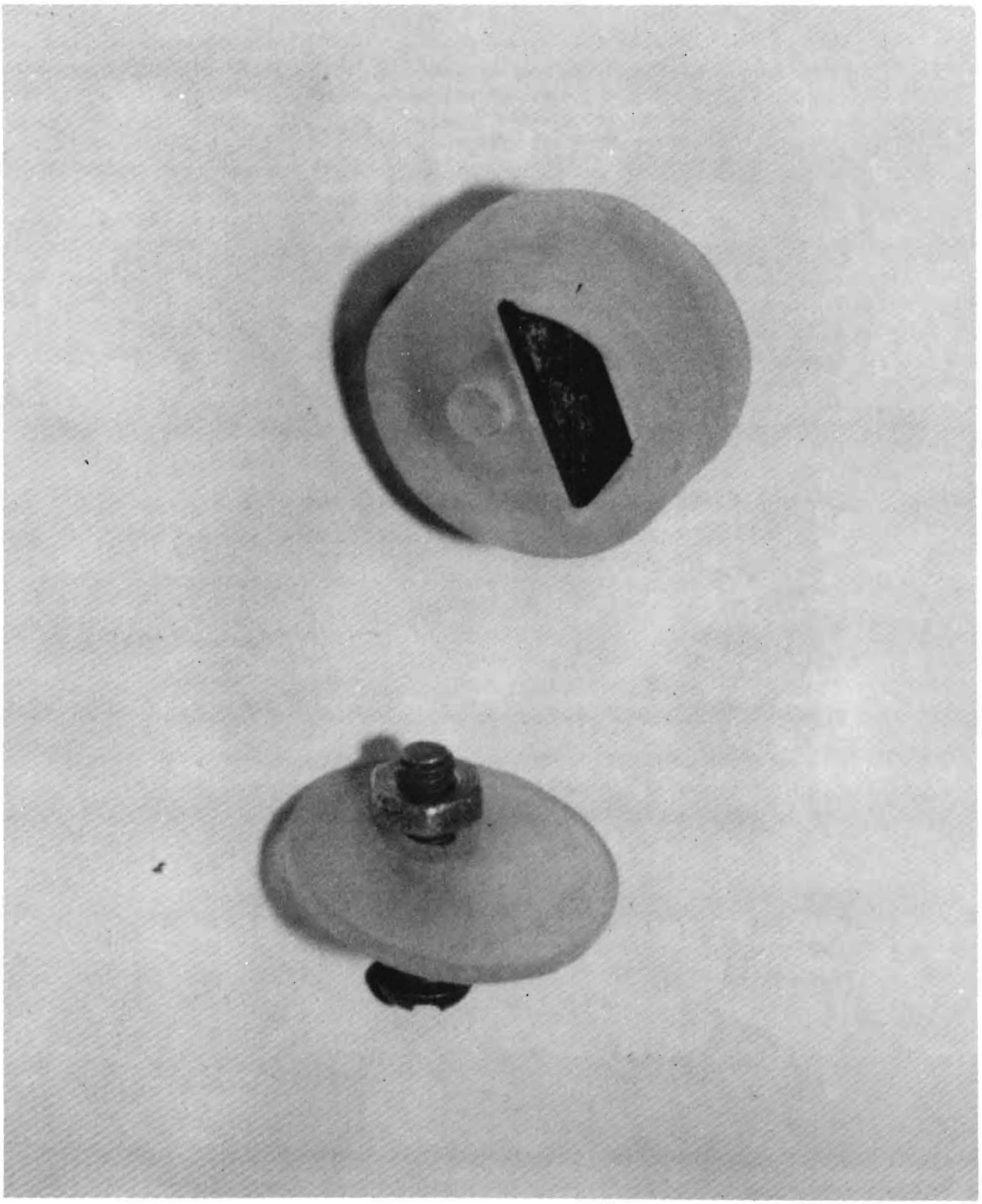

Figure 4. Centrifuge Cell Showing Slide in Place.

cell which had also been conditioned at the same humidity. Finally the cell was closed, sealed, and placed in the centrifuge. The centrifuge was then slowly brought up to the desired speed. This rate was held for approximately one minute, but the time was not found to be critical as long as it exceeded a few seconds. After this brief period the centrifuge was allowed to decelerate unhampered to avoid any effects due to sharp braking.

The slide was carefully removed from the cell and the size distribution of the particles remaining on it was determined. Usually at least 200 particles were measured, but in some cases a lesser number had to suffice because there were not this many particles left on the slide after centrifugation. After the measuring, the slide and centrifuge cell were again placed in the controlled-humidity box for conditioning an additional four hours following which they were centrifuged at a higher speed. This process was repeated a number of times for each slide.

From a graph comparing size distribution curves obtained at several speeds, the per cent of each size particle adhering after each centrifugation was ascertained. This type of graph is shown in Figures 5 and 6.

C. Specific Experiments

1. Glass Spheres on Various Surfaces

Although glass spheres are far from typical of particles found in natural situations, they were used to simulate the ideal case in order to make force calculations and to set a standard for comparing other types of particles. A mixture of spheres varying from 5 to 180 μ in diameter was prepared from Superbrite glass beads of the Minnesota Mining and Manufacturing Company, Minneapolis, Minn. They were washed in Alconox solution, rinsed with distilled water, and dried at 100° C before being used.

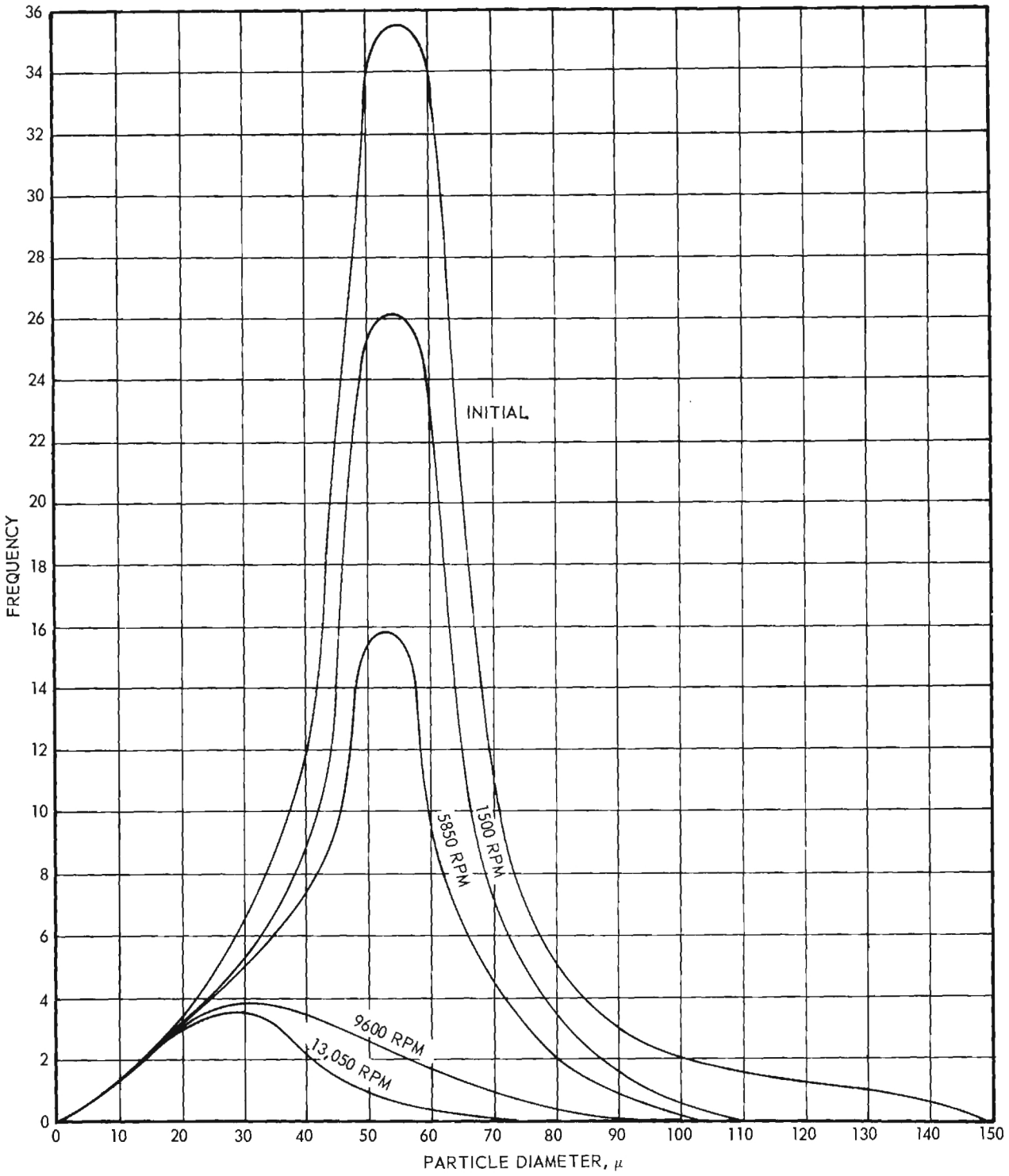

Figure 5. Size Distribution of Glass on Plexiglas before and after Centrifugation at Several Speeds.

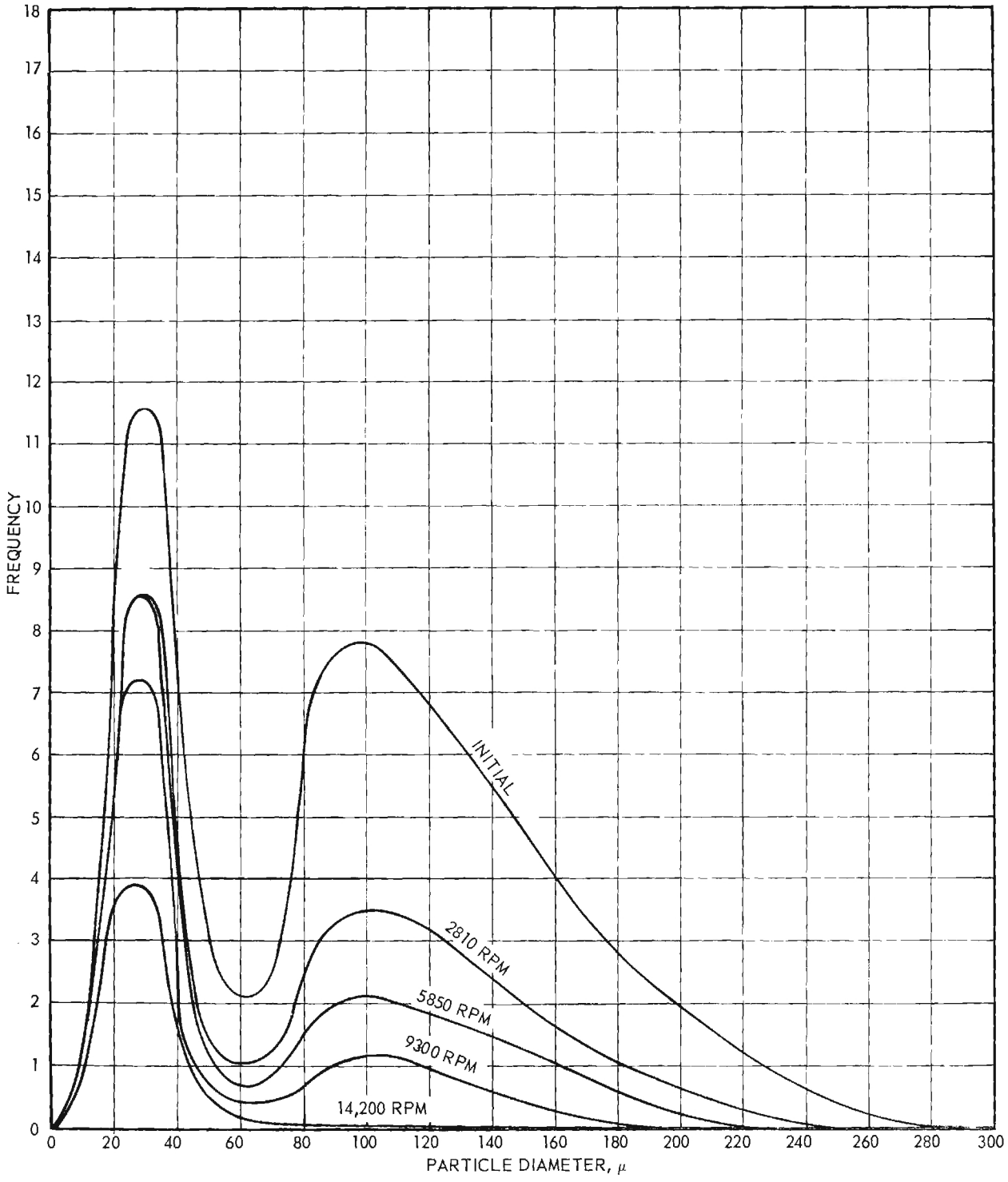

Figure 6. Size Distribution of Sand on Aluminum before and after Centrifugation at Several Speeds.

The adherence of glass beads to surfaces of glass, enamel, Teflon, Micarta, and aluminum at 10 per cent relative humidity, to aluminum, brass, copper, enamel, glass, Micarta, Plexiglas, and Teflon at 50 per cent relative humidity, and to aluminum, brass, brick, enamel, glass, holly leaf, Plexiglas, Teflon and hardwood at 90 per cent relative humidity was studied. The solid surfaces also were washed with Alconox solution, rinsed, and dried before use except the brick, holly leaf, and hardwood. The leaf was used in its natural state, and the brick and hardwood surfaces were sanded until they had a smooth appearance (macroscopic). Centrifuge speeds used in the tests varied from 850 to 13,900 revolutions per minute. From graphs of the type illustrated in Figure 5, the per cent of particles remaining after successive centrifugations was determined for several different sizes of particles. These results are presented in Tables XI through XXXIV.

2. Charcoal Particles on Various Surfaces

A sample of charcoal with particles varying from 5 to 300 μ in diameter was prepared by crushing and screening larger pieces of charcoal. The charcoal particles were very irregular in shape. Experiments utilizing charcoal were made at 10 per cent and 50 per cent relative humidity on glass surfaces, and at 90 per cent relative humidity on aluminum, brass, enamel, glass and Teflon surfaces. The data obtained are presented in Tables XXXV through XLII as per cent of particles remaining attached.

3. Rubber Particles on Glass and Plexiglas

Rubber particles ranging in size from 5 to 300 microns in diameter were made by abrading a neoprene rubber glove with a band saw. The particles produced were very irregular in shape and many of them appeared to be in firmly bound aggregates, but aggregates of rubber or of any of the other

materials used in this investigation were not considered even if they appeared during the making of size distribution determinations. The adhesion of rubber particles to glass and to Plexiglas was studied at 90 per cent relative humidity. Data from these studies are presented in Tables XLIII and XLIV as per cent of particles remaining attached.

4. Sand Particles on Various Surfaces

Purified sand was crushed and screened to obtain a sample composed of particles from 5 to 350 μ in diameter. The adhesion of sand to glass, Micarta, and aluminum at 10 per cent and to glass at 50 per cent relative humidity was studied, and its adhesion to aluminum, brass, enamel, glass, holly leaf, Micarta, Plexiglas and wood was studied at 90 per cent relative humidity. Data from these experiments can be found in Tables XLV through LVI.

V. DISCUSSION OF RESULTS

Even a cursory examination of the data in Tables XI through LVI in the Appendix and Figures 5 and 6 shows that every particle size range has representative members that cling to solids with great as well as with little tenacity. The larger particles, having greater masses, experience a greater force tending to pull them away and, as the data show, they are, on the average, removed at lower centrifuge speeds. Because of this variable behavior of individual particles, attempting to evaluate adhesion forces on the basis of single particle data leads to highly erratic results. Considering, however, all particles in a sample population, an orderly and reproducible shift is produced in the size distribution of adhering particles as extractive forces are applied. Distribution data itself, or information applying to particular particle sizes obtained from distribution curves, can thus be treated to give average adhesion patterns. This was the approach of the investigation; the results are developed more fully in following sections.

As will become evident when the results are studied, many types of correlations and numerous calculations are suggested by the data. Those given here are typical of others that might have been prepared.

A. General Treatment of Data

Particles having an effective diameter of 50 μ were chosen for comparing effects of humidity and differences in attraction between materials. One method for doing this was to plot the log of the per cent of 50-μ particles remaining against the speeds of centrifugation, a straight line usually resulting. A centrifugal speed of 5000 rpm was selected as a further condition for comparing data from the experiments. Figure 7, for example, shows this method of treating the data.

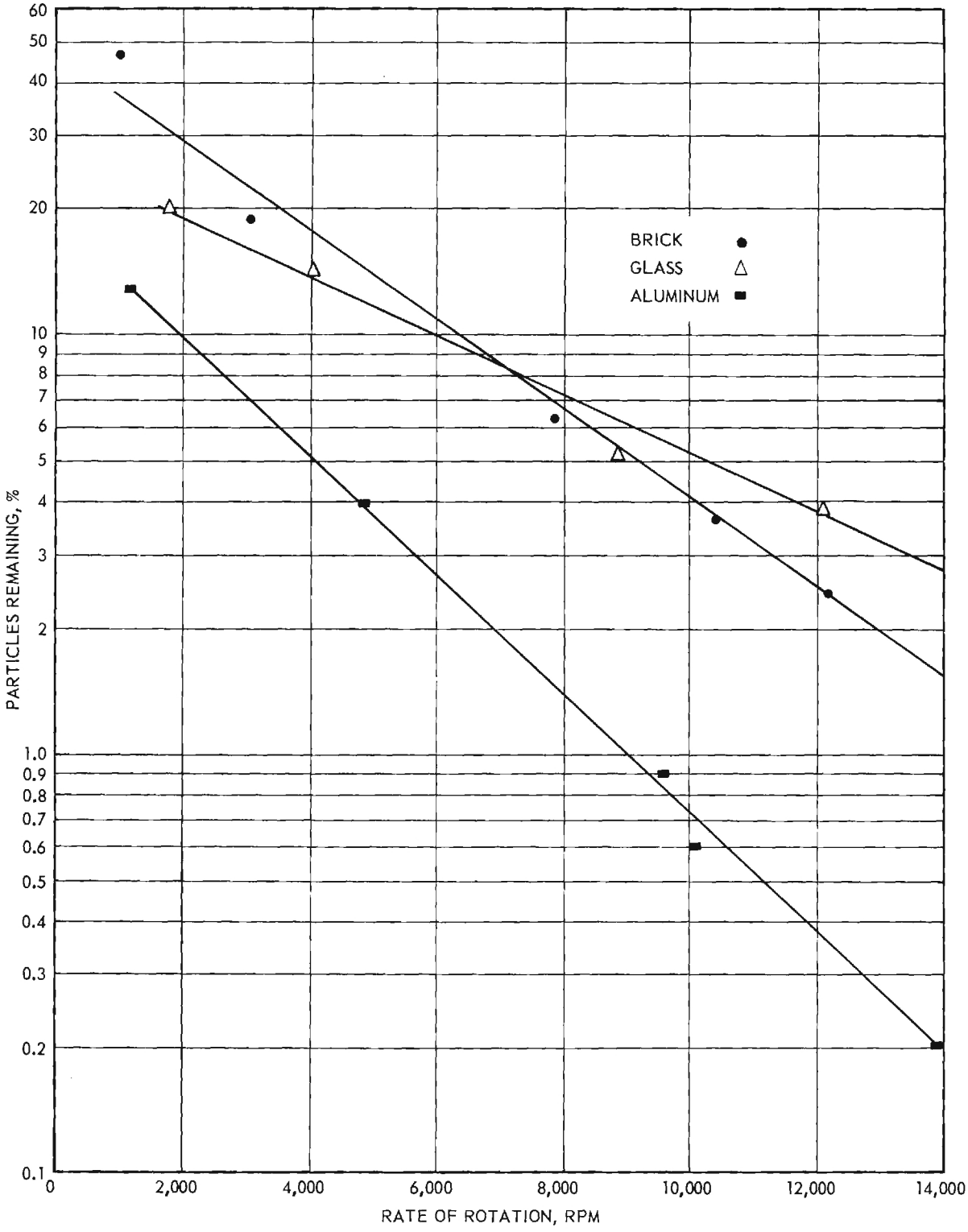

Figure 7. Per Cent of 50-Micron Particles Remaining as a Function of Centrifugal Speed.

The force F required to dislodge particles assumed to be spheres by centrifugation may be calculated from the equation

$$F = D_p^3 \pi (2 \pi \omega)^2 R (\rho/6) \qquad (9)$$

where ρ = particle density,

D_p = diameter of particle larger than 98 per cent of those remaining (in cm),

ω = revolutions per second,

and R = distance from center of rotor to particle location = 5.7 cm in these experiments.

For example, at 11,700 rpm and at 90 per cent relative humidity the value of D_p for glass spheres on a glass plate was found to be 46 μ. The adhesion force F from these data was calculated to be 1.12 dynes. Thus the information is obtained that a force of 1.12 dynes will dislodge 98 per cent of 46-μ diameter glass spheres from a glass plate if the ambient relative humidity is 90 per cent.

B. Humidity

1. Glass Spheres

In the case of glass spheres on a glass surface, measurements, as given in Tables XIII, XXII, and XXX, indicate that the large (80-100 μ diameter) spheres adhere to the surface with a smaller force in the presence of a high humidity atmosphere than they do at lower humidities. This appears to be contrary to the behavior expected for the system. However, the fact that glass normally acquires a negative charge when brought into contact with water, as described in Section III, THEORETICAL TREATMENT OF ADHESION FORCES, may afford a logical explanation. If both sphere and plate develop a negative charge in the presence of a high humidity atmosphere, this would lead to a repulsive force between them. Such a type of force is known to exist in

colloid sols. In these experiments the smaller glass spheres (10-30 μ) adhered somewhat more strongly at high humidities. This difference in humidity effects for different sizes is possibly due to the condition pictured in Figure 1, i.e., the water film surrounds a larger portion of the small spheres than of the large ones. The surface tension of the water then overcomes the repulsion prevailing in the case of the larger spheres.

The adhesion of glass spheres to aluminum surfaces, covered in Tables XI, XVII, and XXVI, was significantly greater at 50 per cent than at 10 per cent relative humidity but decreased at high humidities. This effect may also be due to the opposing effects of water surface tension and the charges that develop on both glass and aluminum in the presence of water. Such a conclusion does not, however, explain the fact that at 90 per cent humidity glass spheres were placed individually on aluminum with great difficulty because they tended to adhere to each other in large clumps. This same agglomeration problem was encountered with a brass plate.

With a relatively weak alpha source employed to dispel electrostatic charges, the adhesion of glass spheres to Teflon in a very dry atmosphere was considerably greater than that found at 50 per cent relative humidity. However, the use of radium D, a more powerful alpha emitter, as an antistatic agent reduced greatly the measured adhesion at 10 per cent relative humidity. At high humidity adhesion was approximately equal to that at 50 per cent humidity but more than at low humidity when radium D was employed. These results suggest that Teflon holds a static charge in dry atmospheres but does not develop an electric charge due to leaching of ions by water in wet atmospheres. These latter results may be seen by examining Tables XV, XXV, and XXXIII.

The adhesion of glass spheres to Micarta, Tables XIV and XXIII, at 10 and 50 per cent relative humidities did not vary greatly. Tests with glass spheres on Plexiglas at 50 and 90 per cent, Tables XXIV and XXXII, also showed no great differences. Neither of these plate materials should acquire an appreciable charge upon contact with water but both can hold electrostatic charges for extended periods.

2. Charcoal, Sand, and Rubber

The force of adhesion of charcoal particles on glass, Tables XXV, XXXVI, and XL, was found to be higher at 90 per cent than at 50 per cent relative humidity, and, for the small sizes at least, still greater at 10 per cent relative humidity. This probably was due to electrostatic charges. However, the largest particles adhered strongest at high relative humidity probably because of the tension of the water film. In the case of sand particles on glass, Tables XLVI, XLVIII, and LII, the effect of humidity is not clearly defined, the maximum adhesion, percentage-wise, being found at different humidities for different sizes. As shown in Figure 6, the sand used in this work had a bimodal distribution and thus probably was composed of particles having two different compositions and reacting differently to changes in humidity.

The adhesion of rubber particles was studied at only one humidity; these results are to be found in Tables XLIII and XLIV.

C. Different Materials

The tendency of glass spheres to adhere to different surfaces varies radically as shown in Table IV. The materials there are listed in what appears to be a decreasing order of adhesion for 50-μ diameter spheres. At 90 per cent relative humidity, glass adheres strongly to wood, followed in

TABLE IV

COMPARISON OF ADHESION OF GLASS SPHERES TO DIFFERENT MATERIALS AS A FUNCTION OF RELATIVE HUMIDITY

Material of Plate	50-μ Spheres Adhering After Centrifuging at 5000 Rpm and 90 Per Cent Relative Humidity (%)	50 Per Cent Relative Humidity (%)	10 Per Cent Relative Humidity (%)
Enamel, Sprayed	--	51	31
Enamel, Brushed	24	45	--
Copper	--	38	--
Wood	47	--	--
Plexiglas	42	38	--
Teflon	18	35	38
Brick	14	--	--
Aluminum	4	18	21
Micarta	--	17	23
Brass	31	10	--
Glass	12	4	1
Holly Leaf	1	--	--
Teflon[a]	--	--	8

[a]Radium D used to remove electrostatic charges.

decreasing order by Plexiglas, brass, enamel, Teflon, brick, glass, aluminum, and holly leaf, which retains only about 2 per cent of the particle concentration retained by wood. At 50 per cent relative humidity, enamel, both sprayed and brushed, has the highest retention of 50-μ spheres, followed by copper, Plexiglas, Teflon, aluminum, Micarta, brass, and glass. At the lowest humidity, Teflon showed the highest adhesion, followed by sprayed enamel, Micarta, aluminum, Teflon when used with radium D to disperse static charges, and glass. The data do not show it, but the initial concentration of spheres on the metallic plates was much less than on all the other materials, i.e., it was more difficult to induce adhesion on metals. In the microscope it could be seen also that the spheres on the metallic surfaces were often resting in scratches or other imperfections, so it would seem that an important factor in the adhesion of glass to aluminum, copper, and brass is surface roughness.

The adhesion of sand particles to different materials following 5000 rpm centrifugation was studied at 90 per cent relative humidity; these data are given in Table V. As shown there the adhesion of 50-μ diameter particles was greatest on wood followed by Micarta, aluminum, enamel, holly leaf, Plexiglas, and glass in that order. Charcoal was similarly tested on different surfaces at 90 per cent relative humidity. The order obtained for adhering 50-μ diameter particles was, first, aluminum, then glass, Plexiglas, Teflon, and brass as shown in Table VI.

In general, the adhesion force between glass spheres and enamel surfaces, as presented in Tables XII, XX, XXI, and XXIX, is large. Enamel applied with a brush seems to give the higher adhesion values, possibly due to a rougher surface.

TABLE V

COMPARISON OF ADHESION OF SAND PARTICLES TO DIFFERENT MATERIALS AT 90 PER CENT RELATIVE HUMIDITY

Material of Plate	50-μ Spheres Adhering After Centrifugation at 5000 Rpm (%)
Wood	56
Micarta	50
Aluminum	45
Enamel	45
Holly Leaf	25
Plexiglas	25
Glass	2

TABLE VI

COMPARISON OF ADHESION OF CHARCOAL PARTICLES TO DIFFERENT MATERIALS AT 90 PER CENT RELATIVE HUMIDITY

Material of Plate	50-μ Particles Adhering After Centrifugation at 5000 rpm (%)
Aluminum	23
Glass	15
Plexiglas	15
Teflon	10
Brass	7

Comparison of the capability of 50-μ diameter glass spheres and irregular particles of sand, charcoal, and rubber to adhere following 5000 rpm centrifugation on a glass surface at 90 per cent relative humidity indicates that rubber adheres more strongly than charcoal. Glass follows next in decreasing order, while the lowest value was found with sand. The results are tabulated in Table VII for convenience. This order corresponds with that which would be predicted on the basis of the elastic or plastic properties of these materials except in the case of glass and sand. These two are very similar chemically and would be expected to give similar values for adhesion except for their differences in shape.

The adhesion of these same four types of particles on Plexiglas, as shown in Table VIII, follows the logical order except for glass, which adheres more strongly than expected. At 50 per cent relative humidity the adhesion of 50-μ glass and sand was identical. Since rubber was not tested at this humidity, the charcoal adhered most strongly, the results apparently corresponding to the elastic properties of the materials.

D. Particle Size

In general, large particles are removed from a surface more readily than small ones. The influence of particle shapes is important here, however, as a flat particle having a large area of contact with a flat surface will adhere more strongly than a small sphere having only a small area of contact. Even in such a case as described, generalizations may be unrealistic, however, as an apparently smooth, flat surface may actually have crevices into which small particles could fit, while the contact area of a flat particle would be reduced because of crevices or ridges. Table IX shows typical results arranged to show the effect of particle size.

TABLE VII

COMPARISON OF ADHESION OF GLASS SPHERES AND PARTICLES OF SAND, CHARCOAL, AND RUBBER ON A GLASS SURFACE AT 90 PER CENT RELATIVE HUMIDITY

Particle Material	50-μ Particles Adhering After Centrifugation at 5000 Rpm (%)
Rubber	18
Charcoal	15
Glass	12
Sand	1.4

TABLE VIII

COMPARISON OF ADHESION OF GLASS SPHERES AND PARTICLES OF SAND, CHARCOAL, AND RUBBER ON A PLEXIGLAS SURFACE

Particle Material	50-μ Particles Adhering After Centrifugation at 5000 Rpm and	
	90 Per Cent Relative Humidity (%)	50 Per Cent Relative Humidity (%)
Glass	42	4
Rubber	34	--
Charcoal	15	11
Sand	13	4

TABLE IX

EFFECT OF PARTICLE SIZE ON ADHESION TO A GLASS SURFACE AT 50 PER CENT RELATIVE HUMIDITY

Effective Diameter of Particle (μ)	Particles of Indicated Size Adhering After Centrifugation at 5000 Rpm at 50 Per Cent Relative Humidity		
	Glass (%)	Sand (%)	Charcoal (%)
100	5	1	0
90	9	1	0
80	13	1	5
70	11	3	10
60	4	4	17
50	4	4	12
40	17	5	13
30	30	14	20
20	88	60	34
10	100	98	92

E. Forces of Adhesion

In this work, particles were removed from flat surfaces by centrifugal force. Other investigators have used different methods of dislodging particles. Jordan,[14] for example, used jets of air to blow glass and quartz dust from glass plates, and also calculated the effect of shaking and concussions in removing small particles from surfaces. He found that 10-μ diameter glass

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[14] D. W. Jordan, "The Adhesion of Dust Particles," British Journal of Applied Physics, Supp. No. 3, S194-197 (1954).

particles (irregular, not spheres) were 95 per cent removed by an air flow of 50 meters per second. To calculate the acceleration required to remove a particle by shaking, he equated the acceleration force a and the adhesion or van der Waals force F, since a particle is sure to stick until a becomes greater than F. From the resulting equation

$$F = 212\, D_p = \pi \rho D_p^3 a/6 \qquad (10)$$

where F = adhesion force in dynes,

D_p = particle diameter in cm,

ρ = density = 2.49 gm/cm^3 for the glass spheres of this investigation,

and a = acceleration perpendicular to the surface in cm/sec,^{2}

the acceleration required to remove a 10-μ diameter glass sphere by shaking is calculated to be $1.6 \times 10^8 \frac{cm}{sec^2}$.

Larsen[15] compared the movement of glass spheres attached to a fiber and subjected to the drag force of an air stream with the movement of the same spheres by centrifugal force. He found the velocity head required to blow particles off the fiber to be given by

$$H_1 = \frac{60{,}000}{D_p\ 1.5} \qquad (11)$$

where H_1 = air velocity head in inches of water,

and D_p = particle diameter in microns.

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[15]Ralph I. Larsen, op. cit.

According to this a 10-μ diameter sphere would require a velocity head equivalent to 1900 inches of water for removal.

Larsen also placed particles on an oil-coated fiber and caused the latter to vibrate. He related the frequency, amplitude of vibration, particle size, and particle density to the dislodging force acting upon the particles by the equation

$$F = 2.06 \times 10^{-11} \rho_s D_p^3 h f^2 \qquad (12)$$

where F = dislodging force in dynes,

ρ_s = particle density in gm/cm,^{3}

D_p = particle diameter in microns,

h = vibration amplitude in cm,

and f = vibration frequency in cycles/sec.

In previous work at Georgia Tech,[16] forces required to remove glass spheres from the tips of pointed metal rods inserted axially into jets of air were investigated, the force being given by

$$F_r = \frac{f_d A \rho_g V^2}{2} \qquad (13)$$

where F_r = force to remove the particle,

f_d = drag coefficient given by Brown et al.[17] as a function of Reynolds Number,

A = particle cross-sectional area,

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[16] C. Orr, Jr. and J. M. Dalla Valle, Studies and Investigations of Agglomeration and Deagglomeration of Solid Particles, Semifinal Report, Project A-233, Georgia Institute of Technology, Engineering Experiment Station, Atlanta, June 30, 1956.

[17] G. G. Brown and Associates, Unit Operations, John Wiley and Sons, Inc. New York, 1950.

ρ_g = air stream density,

and V = air velocity.

While a considerable number of measurements were made, they refer to forces tending to slide or roll the particle along a surface and are not strictly comparable with the forces measured in this investigation. It will suffice to state that spheres having diameters between 25 and 50 μ generally were removed by calculated shearing forces of the order of 0.1 to 0.01 dyne.

Using equation 9 and data from the tables of the Appendix, representative adhesion values for various combinations of particles and surfaces were calculated. Some of these are given in Table X.

Taking as a typical result an adhesion force of 0.74 dyne for a 50-μ diameter sand particle at 50 per cent relative humidity on a glass surface, it is easily shown by equation 10 (actually applicable to quartz only) that this corresponds rather well with a calculated force of 212 x 0.0050 = 1.06 dynes. The same equation shows that an acceleration of 4.5×10^6 cm/sec^2 or 4600 times the normal acceleration of gravity would be required to dislodge the sand particle. Since the dislodging acceleration depends inversely on the cube of particle diameter, it is easily seen that much greater accelerations are required to dislodge smaller particles.

The velocity that a wind blowing along a surface must have in order to dislodge a particle from the surface may be estimated from fluid mechanical considerations. The force exerted on a particle by a moving air stream may be calculated from

$$F = f_d A \rho u^2/2 \qquad (14)$$

TABLE X

FORCES REQUIRED TO REMOVE 98 PER CENT OF 50-μ DIAMETER PARTICLES FROM VARIOUS SURFACES

Identification of Materials		Force Required to Removed 98 Per Cent of Particles at		
Particle	Solid Surface	90 Per Cent Relative Humidity (dynes)	50 Per Cent Relative Humidity (dynes)	10 Per Cent Relative Humidity (dynes)
Glass[a]	Aluminum	0.50	1.35	1.06
"	Enamel, brushed	3.63	6.26	---
"	Enamel, sprayed	---	2.23	2.80
"	Glass	1.83	0.37	0.15
"	Micarta	---	0.65	0.96
"	Plexiglas	1.97	1.44	---
"	Teflon[b]	---	---	0.62
"	Teflon	1.28	0.65	4.15
Sand[c]	Aluminum	6.60	---	1.37
"	Brass	0.45	---	---
"	Enamel, brushed	6.34	---	---
"	Glass	0.06	0.74	1.21
"	Holly Leaf	2.78	---	---
"	Micarta	7.77	---	3.29
"	Wood	12.56	---	---
Charcoal[d]	Aluminum	0.97	---	---
"	Brass	0.32	---	---
"	Enamel, brushed	2.30	---	---
"	Glass	0.94	0.55	1.19

(Continued)

TABLE X (Continued)

FORCES REQUIRED TO REMOVE 98 PER CENT OF 50-μ DIAMETER PARTICLES FROM VARIOUS SURFACES

Identification of Materials		Force Required to Removed 98 Per Cent of Particles at		
Particle	Solid Surface	90 Per Cent Relative Humidity (dynes)	50 Per Cent Relative Humidity (dynes)	10 Per Cent Relative Humidity (dynes)
Charcoal[d]	Plexiglas	0.70	----	----
"	Teflon	0.34	----	----
Rubber[e]	Glass	0.81	----	----
"	Plexiglas	1.93	----	----

[a]Specific gravity, 2.49.

[b]Irradiated with Radium D.

[c]Specific gravity, 2.62.

[d]Specific gravity, 1.23.

[e]Specific gravity, 1.42.

where F = the force on the particle,

A = cross-sectional area of the particle,

ρ = fluid density,

u = velocity of wind impinging on the particle,

and f_d is a drag coefficient, which for laminar flow is given by

$$f_d = \frac{24\ D\ u}{\nu} \tag{15}$$

where D = particle diameter,

and ν = fluid viscosity.

The wind velocity near a surface is not uniform due to the drag of the surface, hence the velocity actually acting on the particle must be calculated. This may be accomplished using an expression for the wind velocity profile along a surface given, according to Eckert,[18] by the relationship

$$\frac{u}{u_s} = \frac{3}{2}\left(\frac{D_p}{\delta}\right) - \frac{1}{2}\left(\frac{D_p}{\delta}\right)^3 \qquad (16)$$

where u = wind velocity at any point outward from the surface,

u_s = free stream velocity,

D_p = particle diameter,

and δ, the boundary layer thickness along the plate, is given for laminar conditions within the boundary by

$$\delta = \frac{4.64\, x^{1/2}\, \nu^{1/2}}{u_s^{1/2}} \qquad (17)$$

where x = distance along surface from the leading edge,

and ν = fluid viscosity.

Substituting equation 15 into equation 14 and differentiating gives

$$dF = 9\pi \frac{D_p^3 \rho u^2}{\nu}\, du. \qquad (18)$$

Differentiating equation 16 gives

$$du = \left(u_s \frac{3}{2\delta} - \frac{3 D_p^2}{2 \delta^3}\right) dD_p. \qquad (19)$$

Substituting equation 19 into equation 18, simplifying, and integrating leads to the expression

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[18] E. R. G. Eckert, Introduction to the Transfer of Heat and Mass, McGraw Hill Book Co., Inc., New York, 1950.

$$F = \frac{9 \pi u_s^3 \rho}{8 \nu} \left[\frac{27 D_p^6}{6 \delta^3} - \frac{45 D_p^8}{8 \delta^5} + \frac{21 D_p^{10}}{10 \delta^7} - \frac{3 D_p^{12}}{12 \delta^9} \right] \qquad (20)$$

the last three terms of which are negligible for the present purpose. Evaluating equation 20, using the properties of air at normal conditions, for the 50-μ diameter sand particle adhering to glass with a force of 0.76 dyne and assumed to be 12 inches from the edge of the surface gives a wind velocity of approximately 100 mph to overcome the adhesion. The validity of this method of calculation was checked by evaluating the Reynolds Number, the criterion of laminar flow in the boundary layer, expressed by $u_s \, x/\nu$. According to Schlichting[19] if this number in the free stream above the particle position does not exceed a value of 3.2×10^5 a laminar layer is sure to exist. This condition was fulfilled in the present calculation.

As in the previous example of acceleration, much higher wind velocities would be required to dislodge smaller particles. It must not be forgotten, however, that both calculations were made using force values that would remove 98 per cent of the particles. The calculations would show correspondingly lower figures if a 50 per cent or even a 90 per cent removal value were used.

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[19] H. Schlichting, Boundary Layer Theory, McGraw Hill Book Co., Inc., New York, 1955.

VI. CONCLUSIONS

The force of adhesion between a particle and a surface exposed to the atmosphere results primarily from a combination of the following, acting simultaneously: (1) London-van der Waals forces, (2) surface tension forces of condensed water films, (3) static electric attraction at low humidity, and (4) either electric repulsion or attraction at high humidity caused by ions leached from the solid or particle by the water film. If static electricity could be completely eliminated at low humidities, the adhesion of materials would be relatively low, corresponding to the London-van der Waals forces. In a natural situation, however, such as a dry wind blowing against a building, elimination of electrostatic forces is impossible and the resulting particle adhesion may be very high.

At high humidities the forces of adhesion vary considerably with the types of materials comprising both particles and flat surface. The force of adhesion is especially high if the particles and the surface are composed of materials which acquire ionic charges opposite in sign in the presence of water. Even in the absence of ionic electric charges, the surface tension of the water film contributes a rather large force if both particle and flat surface are wet by the water. This influence, of course, is much less when one of the materials is not wet by water.

Of the various surfaces tested, enamel-painted and unpainted wood hold particles the most tenaciously. The surfaces from which particles were most readily removed were aluminum and brass and not, surprisingly, Teflon, which is supposed to have a low surface energy. Glass, which loses particles of the 50-μ diameter sizes readily, retains a much higher population of the smaller particles than do aluminum and brass.

Even though a 50-μ diameter particle as used for most of the correlating efforts is much larger than the average airborne mote it has been shown that rather violent mechanical means must be employed to ensure its breaking away from a surface. Smaller particles require proportionally larger forces, so that particles smaller than 10 μ in diameter adhere tenaciously. Among natural phenomena only rainfall probably removes them to any great extent.

VII. RECOMMENDATIONS

In any future study it is recommended that the initial force with which contact between particles and a flat surface is made be investigated to determine its effect on the force of adhesion ultimately developed. This could be accomplished by placing particles on plates with varying pressures and then determining the extent of their removal under the influence of centrifugal force. Also, the nature of adhesion in very moist atmospheres should be studied explicitly. In such a study, for instance, the adhesion at high humidities of particles to surfaces when both were preconditioned in very moist air before contact could be compared with adhesion at high humidities of particles to surfaces when both were preconditioned in a very dry atmosphere before contact with each other. By judicial selection of surface materials, particles, and experimental conditions, the contributions of the surface tension of water, the electric charge developed by some materials in the presence of water, and other factors may be identified. Surface roughness might be investigated by deliberately forming grooves, ridges, or craters on flat plates. The influence of contact potential in the case of metal might well be studied by selecting metals with sufficiently different work functions.

The techniques outlined herein can be readily adapted for making the recommended tests.

Respectfully submitted:

Clyde Orr, Jr.
Project Director

Approved:

W. C. Whitley, Chief
Chemical Sciences Division

J. E. Boyd, Director
Engineering Experiment Station

VIII. APPENDIX

TABLE XI

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON AN ALUMINUM SURFACE EQUILIBRATED AT 10 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		3600 (%)	8100 (%)	12800 (%)	13750 (%)
120	100	0.0	0.0	0.0	0.0
110	99.8	50	0.0	0.0	0.0
100	99.5	60	0.4	0.0	0.0
90	99.0	50	1.8	0.5	0.0
80	95.0	58	1.7	0.5	0.2
70	85.0	48	1.4	0.3	0.2
60	63.0	61	1.2	0.3	0.2
50	27.0	74	2.7	0.5	0.4
40	9.5	70	12	2.8	1.9
30	2.5	77	63	19	12
20	1.0	100	100	79	50
10	0.5	100	100	100	65

TABLE XII

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A SPRAYED ENAMEL SURFACE EQUILIBRATED AT 10 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of 1800 (%)	5300 (%)	9300 (%)
170	100	0.0	0.0	0.0
150	96.7	42	0.0	0.0
120	86.7	42	13	0.0
100	79.3	69	29	4.0
90	54.0	89	33	3.1
80	32.7	86	35	2.8
70	18.7	71	28	3.8
60	8.7	57	29	6.3
50	4.0	54	44	11
40	2.0	65	65	27
30	1.2	91	91	82
20	0.9	100	100	100
10	0.4	100	100	100

TABLE XIII

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A GLASS SURFACE EQUILIBRATED AT 10 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		950 (%)	1800 (%)	6250 (%)	13500 (%)
110	100	0.0	0.0	0.0	0.0
100	99.9	40	0.0	0.0	0.0
90	99.8	56	44	10	0.0
80	99.7	82	64	9.2	0.0
70	98.4	54	38	9.2	0.0
60	97.1	70	6.0	3.0	0.0
50	91.8	18	2.1	0.7	0.0
40	65.2	25	4.7	1.6	0.6
30	31.9	63	7.5	4.7	3.8
20	5.3	100	15	13	13
10	2.0	100	36	36	36

TABLE XIV

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A MICARTA SURFACE EQUILIBRATED AT 10 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		4000 (%)	7200 (%)	11800 (%)	12850 (%)
140	99.8	0.0	0.0	0.0	0.0
100	99.3	54	4.5	0.9	0.0
90	87.4	57	6.8	0.5	0.4
80	82.5	54	6.8	0.3	0.2
70	73.0	52	6.6	0.8	0.1
60	68.2	51	4.0	0.4	0.1
50	40.0	53	5.0	0.7	0.4
40	28.0	59	12	1.9	1.1
30	12.4	72	40	16	12
20	1.5	100	100	59	48
10	0.5	100	100	100	100

TABLE XV

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A TEFLON SURFACE EQUILIBRATED AT 10 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of 1460 (%)	2600 (%)	4000 (%)	4600 (%)	6900 (%)	8700 (%)
190	100	0.0	0.0	0.0	0.0	0.0	0.0
180	99.4	29	4.8	0.0	0.0	0.0	0.0
150	96.6	50	24	0.0	0.0	0.0	0.0
120	88.9	49	15	1.6	0.0	0.0	0.0
110	87.1	54	19	9.1	2.3	0.0	0.0
100	85.9	57	25	22	14	6.8	1.4
90	79.4	65	23	20	13	9.8	1.6
80	54.7	72	50	44	32	20	2.3
70	42.9	89	71	62	57	34	4.7
60	30.0	81	65	55	49	36	9.3
50	20.6	64	64	51	41	35	19
40	14.7	75	75	70	53	38	28
30	9.4	95	95	91	70	70	44
20	5.3	100	100	100	79	79	69
10	2.0	100	100	100	76	76	64

TABLE XVI

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A TEFLON SURFACE EQUILIBRATED AT 10 PER CENT RELATIVE HUMIDITY[a]

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of	
		6200 (%)	9900 (%)
80	97.5	0.0	0.0
70	91.0	2.2	0.0
60	73.5	2.3	0.4
50	41.0	5.1	0.5
40	17.5	29	5.6
30	6.5	100	63
20	1.5	100	100
10	0.5	100	100

[a]Radium D was used to counteract static electricity in these experiments and may have been more efficient than the polonium used during experiments of Table XV.

TABLE XVII

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON AN ALUMINUM SURFACE EQUILIBRATED AT 50 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		3500 (%)	6900 (%)	11100 (%)	13750 (%)
110	100	0.0	0.0	0.0	0.0
100	99.6	13	0.0	0.0	0.0
90	98.1	18	5.9	0.0	0.0
80	97.1	22	3.7	0.9	0.0
70	87.8	18	3.4	1.1	0.3
60	65.4	27	3.9	1.5	0.6
50	25.9	35	7.7	2.0	1.0
40	5.9	56	20	9.1	6.1
30	3.0	100	100	70	44
20	1.0	100	100	100	75
10	0.5	100	100	100	100

TABLE XVIII

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A BRASS SURFACE EQUILIBRATED AT 50 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		3240 (%)	7250 (%)	10380 (%)	12900 (%)
110	100	0.0	0.0	0.0	0.0
100	99.6	5.3	0.5	0.0	0.0
90	98.2	10	2.0	0.8	0.0
80	87.6	11	2.0	0.6	0.2
70	74.6	13	2.4	1.2	0.2
60	54.8	13	2.7	1.0	0.2
50	16.3	17	3.4	1.7	0.4
40	3.8	39	7.7	3.1	1.5
30	1.9	85	30	20	10
20	0.9	100	100	100	56
10	0.4	100	100	100	100

TABLE XIX

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A COPPER SURFACE EQUILIBRATED AT 50 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		3050 (%)	6750 (%)	10700 (%)	12850 (%)
130	99.1	0.0	0.0	0.0	0.0
110	99.0	15	13	9.1	1.8
100	98.9	13	8.4	6.3	3.2
90	96.5	15	8.0	5.1	2.5
80	90.2	18	15	10	3.3
70	82.0	28	22	14	5.6
60	66.1	41	27	14	7.0
50	27.5	48	35	16	7.4
40	5.8	65	51	24	14
30	1.5	88	88	58	42
20	0.5	100	100	80	70
10	0.2	100	100	100	100

TABLE XX

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A DECK ENAMEL SURFACE[a] EQUILIBRATED AT 50 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		3250 (%)	7500 (%)	10850 (%)	12800 (%)
130	99.9	0.0	0.0	0.0	0.0
100	99.4	13	0.0	0.0	0.0
90	98.9	16	8.0	0.0	0.0
80	95.6	18	12	7.0	0.9
70	88.5	29	25	23	12
60	71.4	39	28	23	16
50	25.7	40	31	23	16
40	11.9	69	65	38	30
30	7.6	76	76	39	30
20	1.4	100	88	36	32
10	0.5	100	100	50	50

[a]Applied with a brush.

TABLE XXI

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A SPRAYED ENAMEL SURFACE EQUILIBRATED AT 50 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		4350 (%)	7800 (%)	11400 (%)	13200 (%)
120	99.6	0.0	0.0	0.0	0.0
100	99.1	7.1	3.6	0.0	0.0
90	96.8	16	6.3	0.9	0.0
80	86.9	35	8.5	2.1	0.5
70	78.4	65	13	1.9	0.6
60	55.9	74	22	1.9	0.3
50	17.4	88	39	4.3	1.1
40	8.5	79	69	21	7.5
30	3.3	80	74	49	40
20	1.4	94	83	83	83
10	0.5	100	86	86	86

TABLE XXII

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A GLASS SURFACE EQUILIBRATED AT 50 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of 3210 (%)	7100 (%)	11200 (%)	13100 (%)
110	99.9	0.0	0.0	0.0	0.0
100	99.4	10	0.0	0.0	0.0
90	98.4	33	2.7	0.0	0.0
80	96.4	50	2.8	0.2	0.0
70	93.5	42	1.6	0.3	0.0
60	82.3	18	0.4	0.1	0.0
50	36.3	19	0.5	0.1	0.0
40	17.7	44	2.3	0.7	0.4
30	10.3	52	12	7.5	2.9
20	1.5	89	88	84	80
10	0.5	100	100	100	100

TABLE XXIII

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A MICARTA SURFACE EQUILIBRATED AT 50 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		3350 (%)	6300 (%)	9900 (%)	12200 (%)
130	100	0.0	0.0	0.0	0.0
110	99.5	5.6	0.0	0.0	0.0
100	99.0	25	0.6	0.0	0.0
90	97.6	26	2.9	0.0	0.0
80	90.2	22	2.5	0.1	0.0
70	79.9	30	2.6	0.3	0.1
60	58.2	56	4.1	0.2	0.1
50	12.4	73	5.0	0.4	0.2
40	4.5	92	14	2.6	1.3
30	2.0	100	33	10	4.2
20	0.8	100	67	38	11
10	0.2	100	100	100	39

TABLE XXIV

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A PLEXIGLAS SURFACE EQUILIBRATED AT 50 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of 3500 (%)	8400 (%)	13100 (%)
100	98.9	0.0	0.0	0.0
90	97.5	17	0.0	0.0
80	90.4	25	0.2	0.0
70	82.8	40	0.7	0.0
60	62.3	65	0.8	0.0
50	17.6	93	3.2	0.0
40	8.1	100	38	1.4
30	3.8	100	62	20
20	1.0	100	70	50
10	0.5	100	100	100

TABLE XXV

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A TEFLON SURFACE EQUILIBRATED AT 50 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		3210 (%)	6850 (%)	9900 (%)	12850 (%)
150	100	0.0	0.0	0.0	0.0
140	99.6	20	0.0	0.0	0.0
120	98.6	30	0.0	0.0	0.0
100	97.6	27	0.0	0.0	0.0
90	95.1	28	0.0	0.0	0.0
80	92.1	28	0.1	0.0	0.0
70	81.2	39	4.3	0.1	0.0
60	63.3	72	19	0.1	0.0
50	30.9	72	21	0.1	0.1
40	6.5	78	35	0.9	0.6
30	2.5	100	89	18	7.1
20	1.0	100	100	62	35
10	0.5	100	100	100	100

TABLE XXVI

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON AN ALUMINUM SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY[a]

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of				
		1200 (%)	4900 (%)	9600 (%)	10100 (%)	13900 (%)
100	100	15	0.0	0.0	0.0	0.0
90	98.8	13	2.6	0.0	0.0	0.0
80	93.4	8.3	3.3	1.3	0.4	0.0
70	89.0	4.2	3.1	1.0	0.6	0.2
60	69.0	4.9	4.0	0.6	0.4	0.2
50	42.3	13	4.0	0.9	0.6	0.2
40	26.7	23	5.6	1.1	0.8	0.3
30	16.7	33	14	2.1	1.3	0.8
20	6.7	76	15	6.3	4.4	3.8
10	2.5	100	13	10	9.8	7.5

[a]Samples of glass spheres were placed on aluminum with great difficulty, as the spheres tended to stick to each other more than to the aluminum.

TABLE XXVII

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A BRASS SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of 850 (%)	3260 (%)	6750 (%)	9150 (%)
140	99.2	8.4	0.0	0.0	0.0
120	98.6	35	18	0.0	0.0
100	97.2	42	27	0.0	0.0
90	94.3	61	36	8.7	0.0
80	91.4	82	45	18	3.0
70	85.7	85	56	20	3.8
60	71.4	87	65	18	2.3
50	32.8	74	74	39	7.4
40	28.5	91	91	76	33
30	17.1	84	84	74	52
20	10.0	78	78	70	62
10	2.9	90	90	88	85

TABLE XXVIII

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A BRICK SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of				
		1050 (%)	3080 (%)	7900 (%)	10400 (%)	12200 (%)
120	100	14	0.0	0.0	0.0	0.0
110	99.2	20	0.0	0.0	0.0	0.0
100	98.8	18	0.0	0.0	0.0	0.0
90	98.0	16	0.0	0.0	0.0	0.0
80	97.1	21	2.4	0.0	0.0	0.0
70	96.5	29	7.3	1.8	0.0	0.0
60	94.0	36	16	4.2	2.0	1.0
50	86.0	47	19	6.3	3.6	2.4
40	67.0	52	30	7.9	4.1	3.1
30	35.5	77	54	37	20	19
20	9.5	100	76	69	42	41
10	1.0	100	100	100	100	94

TABLE XXIX

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A BRUSHED ENAMEL SURFACE[a] EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		2000 (%)	4950 (%)	9800 (%)	13000 (%)
130	100	0.0	0.0	0.0	0.0
120	99.8	7.3	1.0	0.0	0.0
110	99.4	33	17	8.3	2.5
100	99.0	30	17	13	3.3
90	97.0	16	11	16	2.4
80	89.0	8.5	5.7	4.0	2.3
70	78.0	8.3	7.0	3.8	2.5
60	58.0	30	25	14	6.6
50	29.0	30	23	13	6.2
40	4.5	33	18	12	7.0
30	1.0	91	50	21	17
20	0.3	100	40	35	35
10	0.2	100	67	67	67

[a]Applied with a brush.

TABLE XXX

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A GLASS SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		1860 (%)	4100 (%)	8900 (%)	12050 (%)
110	99.0	0.0	0.0	0.0	0.0
100	98.5	10	0.0	0.0	0.0
90	97.0	5.6	0.0	0.0	0.0
80	93.0	3.5	1.7	0.0	0.0
70	86.0	3.8	1.1	0.5	0.0
60	66.0	7.9	4.9	1.2	0.3
50	24.0	20	14	5.2	3.8
40	11.0	65	45	28	23
30	6.5	100	85	80	76
20	2.0	100	100	100	100
10	0.5	100	100	100	100

TABLE XXXI

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A HOLLY LEAF EQUILIBRATED AT 82 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		900 (%)	3600 (%)	6000 (%)	9000 (%)
100	100	5.0	0.0	0.0	0.0
90	99.0	3.2	0.5	0.0	0.0
80	93.5	19	4.6	0.0	0.0
70	86.0	1.1	0.6	0.1	0.0
60	66.5	0.6	0.5	0.1	0.0
50	23.5	2.7	2.5	0.2	0.0
40	6.5	23	20	5.7	0.5
30	2.5	93	71	67	16
20	1.0	100	72	72	45
10	0.4	100	100	100	100

TABLE XXXII

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A PLEXIGLAS SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of 1500 (%)	5850 (%)	9600 (%)	13050 (%)
110	99.6	0.0	0.0	0.0	0.0
100	99.2	29	7.3	0.5	0.0
90	96.2	51	30	1.0	0.0
80	92.2	63	39	7.8	0.0
70	89.2	61	39	8.3	0.6
60	72.4	68	28	5.1	1.2
50	36.8	75	46	7.8	2.7
40	26.8	76	63	30	18
30	11.0	81	75	59	54
20	2.0	98	98	98	95
10	0.7	100	100	100	100

TABLE XXXIII

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A TEFLON SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		1630 (%)	5000 (%)	7000 (%)	9300 (%)
110	99.5	0.0	0.0	0.0	0.0
100	99.0	19	0.0	0.0	0.0
90	96.5	24	4.3	0.0	0.0
80	86.5	29	8.1	0.0	0.0
70	76.5	29	14	0.9	0.0
60	53.0	25	23	8.3	0.0
50	17.5	38	35	20	0.7
40	8.0	29	20	19	7.8
30	3.5	61	55	55	48
20	1.0	100	100	100	99
10	0.5	100	100	100	100

TABLE XXXIV

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: GLASS SPHERES ON A WOOD[a] SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of 3000 (%)	8750 (%)	10550 (%)	13000 (%)
100	100	0.0	0.0	0.0	0.0
90	99.8	70	0.0	0.0	0.0
80	98.5	80	7.0	0.0	0.0
70	95.2	76	14	2.6	0.0
60	89.9	68	17	8.1	2.2
50	81.9	74	29	16	6.2
40	72.6	81	53	36	12
30	62.0	87	56	46	11
20	18.0	100	89	77	40
10	5.0	100	100	100	100

[a]Hardwood, sanded.

TABLE XXXV

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: CHARCOAL PARTICLES ON A GLASS SURFACE EQUILIBRATED AT 10 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of		
		4300 (%)	9100 (%)	10850 (%)
110	100	0.0	0.0	0.0
100	99.8	30	0.0	0.0
90	99.5	33	20	0.0
80	99.3	17	8.3	0.0
70	99.0	29	14	0.0
60	98.5	37	13	0.0
50	98.0	53	13	0.0
40	96.5	61	18	0.0
30	88.0	42	33	28
20	68.0	74	43	31
10	18.0	100	81	81

TABLE XXXVI

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: CHARCOAL PARTICLES ON A GLASS SURFACE EQUILIBRATED AT 50 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		3100 (%)	7300 (%)	10900 (%)	13550 (%)
90	99.6	0.0	0.0	0.0	0.0
80	99.5	4.3	0.0	0.0	0.0
70	99.0	25	3.8	0.0	0.0
60	98.5	33	5.0	4.2	0.0
50	95.5	21	3.6	2.9	0.7
40	93.0	21	3.4	2.9	2.3
30	80.0	27	12	10	4.1
20	59.5	39	31	17	12
10	9.5	62	54	32	21
5	4.0	100	100	90	52

TABLE XXXVII

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: CHARCOAL PARTICLES ON AN ALUMINUM SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of				
		1650 (%)	3750 (%)	5500 (%)	8860 (%)	11000 (%)
140	97.0	0.0	0.0	0.0	0.0	0.0
120	96.5	22	6.2	0.0	0.0	0.0
100	96.0	36	9.5	4.8	0.0	0.0
90	91.0	37	16	8.0	4.0	0.0
80	89.5	39	25	8.8	3.5	0.0
70	87.0	38	28	9.4	6.3	0.0
60	85.0	38	31	13	5.6	1.4
50	84.0	43	30	20	12	4.7
40	79.0	45	33	29	23	14
30	73.0	70	50	38	35	22
20	50.5	92	79	29	27	25
10	8.0	100	100	31	27	27

TABLE XXXVIII

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: CHARCOAL PARTICLES ON A BRASS SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of				
		2300 (%)	5250 (%)	8000 (%)	10500 (%)	12950 (%)
200	88.5	0.0	0.0	0.0	0.0	0.0
170	84.5	2.6	0.0	0.0	0.0	0.0
140	77.5	3.8	1.5	0.0	0.0	0.0
120	73.0	5.1	2.9	0.3	0.0	0.0
100	68.0	4.5	2.7	0.8	0.0	0.0
90	64.5	4.6	2.7	1.2	0.0	0.0
80	58.5	6.0	2.4	1.1	0.0	0.0
70	52.0	8.0	2.4	1.0	0.0	0.0
60	48.0	12	2.4	1.4	0.3	0.0
50	42.0	21	5.9	2.1	0.7	0.0
40	34.0	30	10	5.2	2.2	2.0
30	24.0	56	17	13	9.2	6.2
20	8.0	62	39	25	22	13
10	3.0	100	100	98	76	23

TABLE XXXIX

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: CHARCOAL PARTICLES ON AN ENAMEL[a] SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of				
		1200 (%)	4000 (%)	7350 (%)	10300 (%)	13200 (%)
270	98.5	0.0	0.0	0.0	0.0	0.0
240	97.5	7.2	0.0	0.0	0.0	0.0
210	97.0	20	6.6	0.0	0.0	0.0
180	96.5	31	15	4.0	0.0	0.0
150	96.0	33	16	8.5	4.0	0.0
120	94.5	29	15	8.2	1.4	0.0
100	90.5	33	15	11	3.0	0.0
90	85.5	34	15	9.7	3.6	0.8
80	82.0	36	16	10	5.0	0.8
70	79.0	44	21	15	7.3	2.5
60	74.0	51	26	18	9.8	4.9
50	67.5	62	32	22	13	11
40	56.5	80	59	25	21	16
30	37.5	93	82	44	36	25
20	16.5	99	96	57	40	40
10	7.0	100	100	100	46	46

[a]Deck enamel applied with a brush.

TABLE XL

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: CHARCOAL PARTICLES ON A GLASS SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of				
		930 (%)	3060 (%)	6000 (%)	8850 (%)	13350 (%)
160	99.0	0.0	0.0	0.0	0.0	0.0
140	98.5	16	0.0	0.0	0.0	0.0
120	97.0	24	13	1.9	0.0	0.0
100	96.0	24	22	12	0.9	0.0
90	95.5	25	23	15	4.1	0.8
80	95.0	27	21	17	7.7	2.0
70	93.5	36	18	16	9.5	4.0
60	92.5	41	14	12	8.5	5.5
50	88.0	42	15	9.4	5.3	4.0
40	80.5	45	26	17	8.6	4.3
30	73.0	47	29	25	21	5.7
20	53.0	84	78	32	32	13
10	13.0	100	100	38	38	14

TABLE XLI

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: CHARCOAL PARTICLES ON A PLEXIGLAS SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of				
		1480 (%)	4500 (%)	7500 (%)	11550 (%)	13450 (%)
210	99.5	0.0	0.0	0.0	0.0	0.0
180	99.0	12	0.0	0.0	0.0	0.0
150	98.5	14	0.0	0.0	0.0	0.0
120	97.5	16	0.0	0.0	0.0	0.0
100	96.0	18	1.0	0.0	0.0	0.0
90	93.0	17	3.3	0.0	0.0	0.0
80	92.5	18	5.0	1.7	0.0	0.0
70	91.0	23	8.1	3.3	0.0	0.0
60	89.0	29	12	4.5	1.5	0.0
50	85.5	31	19	7.1	2.4	0.0
40	80.0	30	19	8.6	6.4	3.6
30	70.0	15	11	6.8	5.2	3.6
20	35.5	41	43	23	21	12
10	5.0	100	46	39	38	37

TABLE XLII

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: CHARCOAL PARTICLES ON A TEFLON SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		1440 (%)	4500 (%)	7790 (%)	11500 (%)
110	95.0	0.0	0.0	0.0	0.0
100	94.0	1.8	0.0	0.0	0.0
90	93.5	13	1.6	0.0	0.0
80	93.0	26	11	0.0	0.0
70	92.0	42	14	1.7	0.0
60	91.0	62	10	2.1	0.0
50	86.5	72	11	3.4	0.3
40	77.5	70	20	4.5	1.6
30	59.0	69	30	7.4	1.5
20	34.0	87	59	20	7.8
10	4.5	100	100	52	22

TABLE XLIII

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: RUBBER PARTICLES ON A PLEXIGLAS SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		960 (%)	6300 (%)	10600 (%)	13100 (%)
250	100	0.0	0.0	0.0	0.0
240	99.9	57	0.0	0.0	0.0
220	99.4	54	0.0	0.0	0.0
190	98.8	57	0.0	0.0	0.0
160	97.7	60	0.0	0.0	0.0
130	96.6	58	5.3	0.0	0.0
100	93.3	52	3.9	2.0	0.0
90	92.2	55	7.3	3.6	1.8
80	87.8	51	12	4.9	3.3
70	85.6	51	21	7.6	2.1
60	84.5	54	30	9.5	3.0
50	80.1	59	39	16	4.6
40	74.5	61	41	19	5.7
30	71.2	51	35	27	11
20	55.6	56	40	18	12
10	17.8	87	73	24	18

TABLE XLIV

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: RUBBER PARTICLES ON A GLASS SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of 1040 (%)	3300 (%)	6000 (%)	9600 (%)	12600 (%)
250	96.8	0.0	0.0	0.0	0.0	0.0
220	96.1	25	0.0	0.0	0.0	0.0
190	95.4	29	9.5	0.0	0.0	0.0
160	91.9	29	18	0.0	0.0	0.0
130	87.0	29	18	0.0	0.0	0.0
100	80.0	25	15	3.3	0.0	0.0
90	77.9	27	22	15	2.9	0.0
80	74.4	30	16	4.1	1.4	0.5
70	68.7	34	20	4.9	3.7	2.2
60	61.6	41	26	5.4	3.7	3.3
50	58.8	50	34	4.6	3.7	3.3
40	53.1	61	36	5.7	3.6	2.9
30	48.1	54	26	7.4	2.9	2.2
20	29.7	89	36	23	8.8	5.2
10	2.1	100	74	58	10	6.2

TABLE XLV

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: SAND PARTICLES ON AN ALUMINUM SURFACE EQUILIBRATED AT 10 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		3460 (%)	7550 (%)	10700 (%)	13550 (%)
220	98.3	0.0	0.0	0.0	0.0
190	94.0	13	0.0	0.0	0.0
160	87.1	14	2.3	0.0	0.0
130	77.6	11	6.7	0.0	0.0
100	56.0	3.8	2.5	0.0	0.0
90	50.8	6.5	3.6	0.0	0.0
80	44.8	11	6.7	0.3	0.0
70	42.2	15	10	1.9	0.0
60	39.6	20	14	3.6	0.0
50	36.2	24	20	4.3	0.4
40	34.5	28	21	3.8	2.5
30	27.6	40	32	8.3	5.8
20	12.9	80	80	64	28
10	5.0	100	100	80	35

TABLE XLVI

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: SAND PARTICLES ON A GLASS SURFACE EQUILIBRATED AT 10 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of		
		3520 (%)	8600 (%)	12300 (%)
110	41.5	0.0	0.0	0.0
100	32.0	0.3	0.0	0.0
90	27.0	0.5	0.0	0.0
80	23.5	1.5	0.0	0.0
70	21.5	2.8	0.6	0.1
60	20.0	4.1	2.4	1.2
50	18.0	4.4	2.2	1.8
40	16.5	5.7	3.2	2.2
30	13.0	8.1	4.7	3.4
20	7.0	38	34	11
10	2.5	100	100	37

TABLE XLVII

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: SAND PARTICLES ON A MICARTA SURFACE EQUILIBRATED AT 10 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of 4750 (%)	8650 (%)	12550 (%)
100	74.0	0.0	0.0	0.0
90	72.5	5.3	0.0	0.0
80	70.0	29	0.0	0.0
70	60.0	55	1.8	0.0
60	59.0	64	18	0.0
50	58.5	67	33	0.0
40	57.5	71	43	14
30	56.5	71	61	50
20	48.0	77	56	42
10	20.0	94	94	89

TABLE XLVIII

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: SAND PARTICLES ON A GLASS SURFACE EQUILIBRATED AT 50 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		4300 (%)	7500 (%)	12100 (%)	13950 (%)
120	70.5	0.0	0.0	0.0	0.0
110	57.5	0.7	0.0	0.0	0.0
100	42.5	0.8	0.0	0.0	0.0
90	34.0	1.2	0.1	0.0	0.0
80	26.0	2.1	0.4	0.2	0.0
70	22.5	4.2	2.1	0.4	0.0
60	20.0	6.2	3.1	0.6	0.0
50	19.0	6.0	2.4	0.6	0.0
40	15.5	7.2	4.2	1.4	0.1
30	12.5	17	11	5.7	2.9
20	7.5	72	64	31	23
10	3.5	100	94	48	47

TABLE XLIX

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: SAND PARTICLES ON AN ALUMINUM SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		2810 (%)	5850 (%)	9300 (%)	14200 (%)
260	100	0.0	0.0	0.0	0.0
240	97.8	14	0.0	0.0	0.0
210	95.6	31	11	0.0	0.0
180	89.2	38	21	4.8	0.0
150	77.5	44	25	10	1.3
120	61.2	46	26	14	1.3
100	49.4	45	26	15	1.3
90	42.3	43	27	14	1.3
80	34.0	39	34	20	1.6
70	32.2	41	29	15	2.7
60	30.5	51	32	21	4.9
50	27.6	43	33	25	13
40	25.3	77	65	47	27
30	14.1	75	75	62	33
20	4.1	67	67	67	43
10	1.3	100	100	100	100

TABLE L

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: SAND PARTICLES ON A BRASS SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of				
		920 (%)	3210 (%)	5900 (%)	9600 (%)	12800 (%)
290	100	0.0	0.0	0.0	0.0	0.0
280	99.8	1.0	0.0	0.0	0.0	0.0
250	99.0	1.2	0.0	0.0	0.0	0.0
220	95.6	1.3	0.0	0.0	0.0	0.0
190	87.7	1.1	0.1	0.0	0.0	0.0
160	76.8	0.5	0.2	0.1	0.1	0.0
130	56.9	0.3	0.2	0.1	0.1	0.1
100	20.3	0.2	0.1	0.1	0.1	0.1
90	11.7	0.3	0.2	0.1	0.1	0.1
80	5.7	0.7	0.4	0.3	0.2	0.1
70	3.4	1.3	0.7	0.5	0.4	0.2
60	3.0	2.1	1.2	0.9	0.7	0.4
50	2.4	3.5	2.4	2.0	1.7	1.1
40	1.9	6.7	6.2	5.1	3.8	2.8
30	0.8	24	18	14	11	8.2
20	0.5	72	62	57	34	29
10	0.2	100	85	80	70	53

TABLE LI

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: SAND PARTICLES ON A BRUSHED ENAMEL SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of				
		1070 (%)	4950 (%)	8300 (%)	11900 (%)	14100 (%)
270	100	0.0	0.0	0.0	0.0	0.0
260	99.5	33	6.7	0.0	0.0	0.0
230	98.0	50	25	19	9.1	2.7
200	94.5	47	28	16	8.5	2.9
170	83.0	40	23	11	7.6	3.6
140	61.0	41	33	20	13	5.9
110	37.5	42	39	28	20	10
100	31.5	41	37	25	21	12
90	25.5	41	33	22	19	12
80	20.0	51	31	22	18	13
70	16.0	64	32	22	15	12
60	13.0	85	37	24	14	11
50	11.5	89	42	23	14	10
40	11.0	92	34	24	14	10
30	8.0	100	32	27	18	11
20	3.5	100	30	27	19	12
10	1.5	100	100	100	100	100

TABLE LII

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: SAND PARTICLES ON A GLASS SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		1040 (%)	5100 (%)	8000 (%)	12100 (%)
200	95.0	0.0	0.0	0.0	0.0
170	83.5	0.8	0.0	0.0	0.0
140	65.0	0.7	0.0	0.0	0.0
110	35.0	0.7	0.2	0.1	0.0
100	25.0	0.8	0.2	0.1	0.1
90	14.5	0.7	0.3	0.1	0.1
80	10.5	0.9	0.4	0.2	0.1
70	6.5	0.7	0.5	0.2	0.1
60	6.0	0.9	0.5	0.3	0.1
50	5.0	2.1	1.6	1.1	0.5
40	4.0	4.7	3.4	2.5	0.9
30	3.0	13	8.2	6.2	3.4
20	1.5	47	28	25	11
10	0.5	100	52	40	17

TABLE LIII

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: SAND PARTICLES ON A HOLLY LEAF SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		940 (%)	2190 (%)	5750 (%)	8660 (%)
300	97.0	0.0	0.0	0.0	0.0
270	96.0	12	0.0	0.0	0.0
240	95.0	26	1.6	0.0	0.0
210	89.5	36	8.3	0.4	0.0
180	80.5	44	15	5.1	1.2
150	57.5	52	18	8.6	2.5
120	38.0	83	29	19	6.6
100	25.5	82	42	35	11
90	15.5	94	51	42	12
80	13.5	88	69	63	17
70	12.0	78	73	64	19
60	8.5	58	31	29	11
50	8.0	43	29	25	13
40	6.0	57	48	42	28
30	4.5	74	71	55	49
20	1.5	92	78	56	44
10	0.5	100	86	50	43

TABLE LIV

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: SAND PARTICLES ON A MICARTA SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of				
		980 (%)	2785 (%)	6200 (%)	9000 (%)	12800 (%)
310	99.0	0.0	0.0	0.0	0.0	0.0
280	97.5	8.3	0.0	0.0	0.0	0.0
250	95.5	8.3	1.7	0.0	0.0	0.0
220	92.0	25	13	4.2	0.0	0.0
190	89.0	62	10	5.5	1.4	0.0
160	80.5	37	6.1	4.1	1.5	0.2
130	61.0	31	7.8	4.5	2.0	0.5
100	28.5	40	9.0	6.5	3.5	1.5
90	19.5	51	10	8.7	5.0	2.3
80	14.0	66	16	15	8.6	4.5
70	13.5	75	39	34	27	11
60	13.0	79	57	47	19	16
50	12.5	82	71	61	22	17
40	12.0	93	93	92	29	26
30	9.5	100	53	53	41	28
20	4.0	100	44	44	43	23
10	1.5	100	50	42	42	42

TABLE LV

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: SAND PARTICLES ON A PLEXIGLAS SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of				
		1230 (%)	3360 (%)	6250 (%)	9150 (%)	12400 (%)
300	99.8	0.0	0.0	0.0	0.0	0.0
270	99.3	17	0.0	0.0	0.0	0.0
240	98.3	27	0.0	0.0	0.0	0.0
210	97.8	24	1.0	0.0	0.0	0.0
180	93.8	23	5.0	0.5	0.0	0.0
150	84.3	43	7.5	1.7	0.2	0.0
120	60.6	49	15	7.5	5.2	0.3
100	42.4	52	32	13	5.8	0.3
90	29.6	42	39	16	6.6	0.4
80	21.2	41	35	19	8.9	0.7
70	16.3	37	27	20	12	1.5
60	14.3	33	26	20	14	2.4
50	10.9	36	30	23	18	5.0
40	9.9	42	36	26	20	8.0
30	7.4	68	38	35	15	8.1
20	2.5	87	37	29	9.2	7.9
10	1.0	100	31	25	11	8.3

TABLE LVI

PARTICLES ADHERING AS A FUNCTION OF APPLIED CENTRIFUGAL FORCE: SAND PARTICLES ON A WOOD[a] SURFACE EQUILIBRATED AT 90 PER CENT RELATIVE HUMIDITY

Particle Diameter (μ)	Particles Less Than Indicated Size, Before Centrifugation (%)	Particles Continuing to Adhere After Being Subjected to Centrifugation at Rpm's of			
		930 (%)	3300 (%)	6300 (%)	12000 (%)
290	100	16	0.0	0.0	0.0
260	99.8	20	0.0	0.0	0.0
230	98.8	26	17	5.2	0.0
200	95.8	47	30	6.7	0.0
170	91.8	49	27	8.9	0.0
140	80.6	53	17	5.3	0.0
110	51.9	65	21	4.3	0.8
100	42.1	66	28	5.1	0.8
90	29.4	72	35	6.5	1.2
80	20.1	55	40	9.6	2.4
70	13.8	53	49	20	5.0
60	12.3	65	65	53	12
50	10.3	94	94	94	20
40	8.8	100	100	100	32
30	6.4	100	100	100	61
20	2.5	100	100	100	100
10	0.5	100	100	100	100

[a]Hard wood, sanded.

TABLE LVII

TRIGONOMETRIC RELATIONSHIPS

θ (Deg)	$\sin\theta$	$\cos\theta$	$1-\cos\theta$	$h/x = \frac{(1-\cos\theta)}{\sin\theta}$
1	0.01745	0.99985	0.00015	0.00860
2	0.03490	0.99939	0.00061	0.01745
3	0.05234	0.99863	0.00137	0.02615
4	0.06976	0.99756	0.00244	0.03500
5	0.08716	0.99619	0.00381	0.04870
6	0.10453	0.99452	0.00548	0.05250
7	0.12187	0.99255	0.00745	0.06120
8	0.13917	0.99027	0.00983	0.07060
9	0.15643	0.98769	0.01231	0.07870
10	0.17365	0.98481	0.01519	0.08740
11	0.19081	0.98163	0.01837	0.09620
12	0.20791	0.97815	0.02185	0.10550
13	0.22495	0.97437	0.02563	0.11430
14	0.24192	0.97030	0.02970	0.12310
15	0.25882	0.96593	0.03407	0.13200
16	0.27564	0.96126	0.03874	0.14100
17	0.29237	0.95630	0.04370	0.14970
18	0.30902	0.95106	0.04894	0.15800
19	0.32557	0.94552	0.05448	0.16700
20	0.34202	0.93969	0.06031	0.17600
21	0.35837	0.93358	0.06642	0.18600
22	0.37461	0.92718	0.07282	0.19400
23	0.39073	0.92050	0.07950	0.20300
24	0.40674	0.91355	0.08645	0.21300
25	0.42262	0.90631	0.09369	0.22100
26	0.43837	0.89879	0.10121	0.22900
27	0.45399	0.89101	0.10899	0.23890
28	0.46947	0.88295	0.11705	0.25000
29	0.48481	0.87462	0.12538	0.25900
30	0.50000	0.86603	0.13397	0.26760

(Continued)

TABLE LVII (Continued)

TRIGONOMETRIC RELATIONSHIPS

θ (Deg)	$\sin\theta$	$\cos\theta$	$1-\cos\theta$	$h/x = \frac{(1-\cos\theta)}{\sin\theta}$
32	0.52992	0.84805	0.15195	0.28790
34	0.55919	0.82904	0.17096	0.30500
36	0.58779	0.80902	0.19098	0.32400
38	0.61566	0.78801	0.21199	0.34300
40	0.64279	0.76604	0.23396	0.36320
42	0.66913	0.74314	0.25686	0.38500
44	0.69466	0.71934	0.28066	0.40500
45	0.70711	0.70711	0.29281	0.41400